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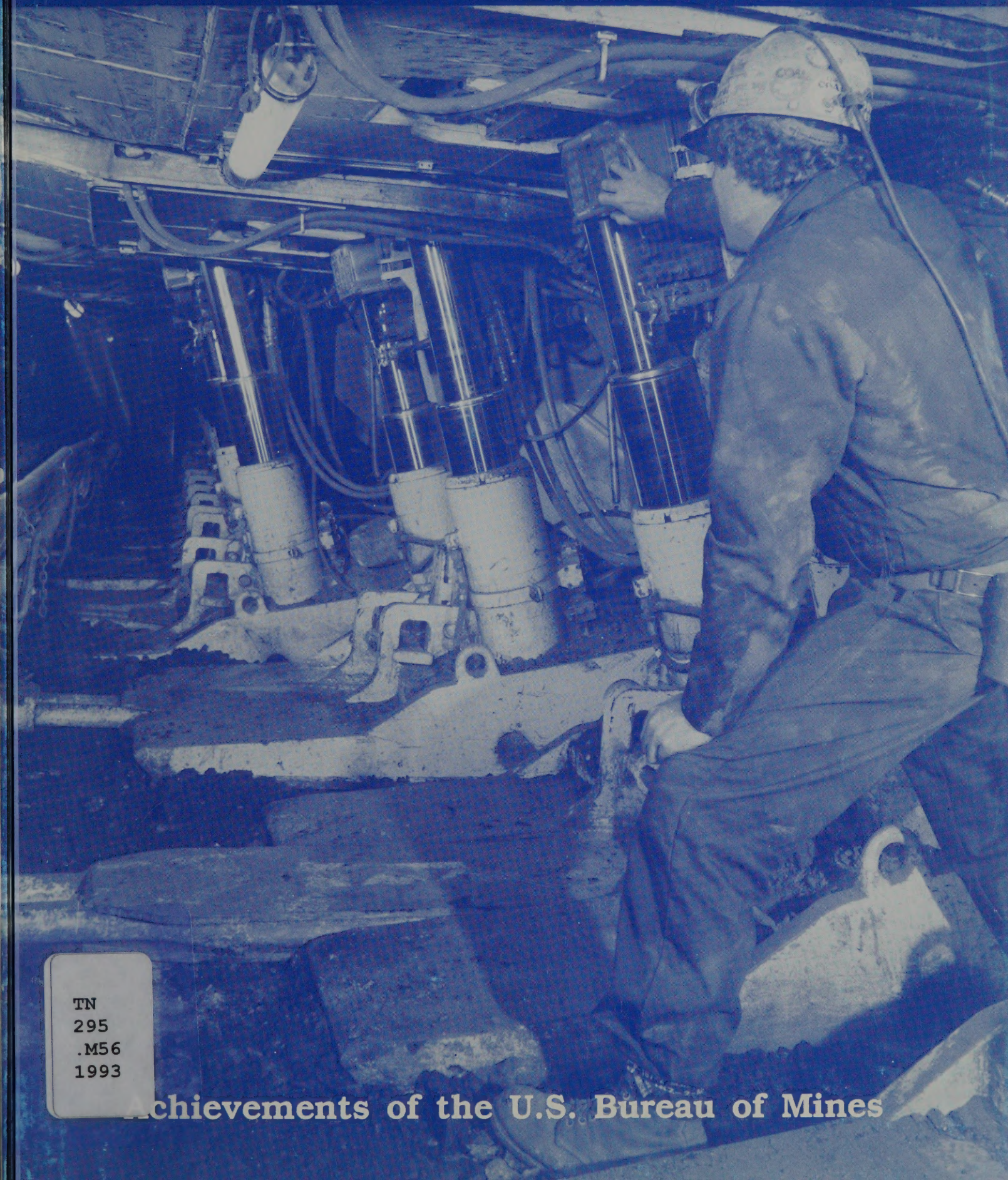
HEALTH AND SAFETY RESEARCH



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Achievements of the U.S. Bureau of Mines

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MINE HEALTH AND SAFETY RESEARCH

Achievements of the U.S. Bureau of Mines

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

1993

Cover photo: *A major thrust of research by the U.S. Bureau of Mines has been toward longwall coal mining systems that will significantly improve the safety and health of the Nation's mineworkers.*

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Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

INTRODUCTION

LEGISLATIVE HISTORY

Since its inception in 1910, the U.S. Bureau of Mines has addressed problems of mine health and safety, as well as the need for improved mining technology. A renewed concern about the working conditions in mines resulted in a significant increase of health and safety research activities in 1970 following passage of the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173). This legislation directed that the Bureau conduct the research necessary to eliminate coal mining hazards and/or provide alternative means of mining that reduce the risks of health impairment, injury, or death. The Federal Mine Safety and Health Amendments Act of 1977 (Public Law 95-164) provided for the first time a single piece of comprehensive legislation for both coal and metal/nonmetal mining operations and extended the research mandates of prior legislation to all segments of the mining industry.

The Bureau also conducts mining technology research under the Organic Act (Public Law 63-283), which mandates research to improve productivity, increase resource recovery, and reduce environmental problems associated with mining. This publication reviews the U.S. Bureau of Mines health and safety research program following the enactment of the Federal Coal Mine Health and Safety Act of 1969 and identifies significant Bureau contributions that are currently in use or expected to be used by the mining sector in the near future.

BACKGROUND

The success of the Bureau's health and safety research program would not be possible without the active participation and cooperation of many mining companies and equipment manufacturers. Participation has been extensive as evidenced by the hundreds of mining companies and other organizations that have entered into formal Memorandums of Agreement with the Bureau of Mines under its health and safety research program since 1970. In addition to these agreements, there are many informal working arrangements between the industry and the Bureau. Without access to the real-world conditions found in active mining operations, basic data cannot be obtained, nor can concepts be evaluated and validated.

In addition to cooperation with individual mine operators, the Bureau has had formal agreements with many industry associations such as the Colorado Mining Association (CMA), the National Industrial Sand Association, the National Coal Association (NCA), and the American Mining Congress (AMC). The cooperative program with CMA, established in 1983, has been directed toward the identification and prevention of potential safety problems in oil shale mining. Through the cooperative effort with the National Industrial Sand Association, exposure of certain personnel in silica bagging plants has been reduced 80% to 90%, bringing these plants into compliance with Federal health and safety regulations. Cooperation and coordination with NCA and other industry associations has improved research program planning, as well as the transfer of developed technology. Initiated in 1986, the agreement with AMC has provided a formalized mechanism for input to the Bureau's research programs from large sectors of the coal and metal/nonmetal industries.

The two principal Federal agencies with which the Bureau interacts relative to health and safety research are the Mine Safety and Health Administration (MSHA) and the National Institute for Occupational Safety and Health (NIOSH). Without their participation, the achievements cited in this publication would not have been possible.

Bureau coordination extends to international organizations as well. These agencies either provide input to or derive benefit directly from the program. The Bureau of Mines cooperates with a number of foreign countries under the national umbrella agreement in science and technology cooperation and through bilateral Memorandums of Understanding. Some of the more active cooperating countries have been Canada, the United Kingdom, Australia, France, Germany, Yugoslavia, and Poland. Other cooperating countries include Belgium, Hungary, Japan, Korea, India, the Republic of South Africa, and the People's Republic of China.

PROGRAM STRUCTURE

The Bureau's health and safety research program has undergone a number of organizational changes since 1970. For the purposes of providing this summary, the following program structure will be used:

- Health research
  - Respirable dust
  - Noise
  - Radiation
  - Industrial hygiene/diesel emission control
- Safety research
  - Ground control
  - Human factors
  - Industrial safety
  - Disaster prevention
    - Methane control
    - Fires and explosions
    - Life support
    - Explosives
    - Mine rescue

The health and safety research program addresses all types of mining—surface, underground, coal, and metal/nonmetal—as well as coal preparation and ore beneficiation facilities. The Bureau's research activities have not addressed medical and epidemiological research. This is accomplished by NIOSH, which also on occasion conducts in-mine assessments of health hazards, as well as joint work with the Bureau to measure health hazards, such as dust particulate exposure. The combined efforts of the two agencies seek to provide solutions to principal health and safety problems of the U.S. minerals industry. Another opportunity for close collaboration in terms of health research needs is with the Bureau-funded Generic Mineral Technology Centers for Respirable Dust, and for Mine Systems Design and Ground Control. The former Center, which consists of specialists from The Pennsylvania State University, West Virginia University, the Massachusetts Institute of Technology, the University of Minnesota, and Michigan Technological University, conducts fundamental investigations as they relate to both the engineering and medical aspects of respirable dust. The latter Center focuses on the fundamental study of engineering designs as they apply to innovative approaches to coal mine extraction.

The Bureau and MSHA coordinate activities in the area of mine health and safety research as required by the Federal Coal Mine Health and Safety Act of 1969 and the Federal Mine Safety and Health Amendments Act of 1977. Coordination of this work is accomplished by a Memorandum of Understanding, which extends from identification of research needs to individual project identification and prioritization. This is accomplished through planning, monitoring, review of draft final reports, and technology transfer of Bureau research programs. MSHA plays an important function regarding in-mine demonstration and

validation of Bureau research results. Related areas of cooperation include Bureau assistance to MSHA for approval and certification of permissible explosives, and investigation assistance for mine disasters. MSHA provides approval and certification of Bureau-developed hardware and equipment.

HEALTH AND SAFETY EXPERIENCE

Death and injuries to coal miners have been reduced as a result of more stringent regulations, enhanced training activities, new technology, and new procedures. It is the latter two areas where the Bureau has been the principal contributor. However, substantial experience with Bureau research results is being used to address standards development and enforcement procedures. Absolute injury and fatality numbers are meaningless. A more meaningful measure of progress is based on exposure frequency. With regard to fatal injuries in the coal mining industry, figure 1 shows there has been a significant decline. Note that from 1965 to 1990 there was a 79% decrease in fatalities per 200,000 employee-hours of exposure and a 7.8% decrease in disabling injuries. It should be noted that from 1972 to 1990 all reportable injuries decreased by 48%.

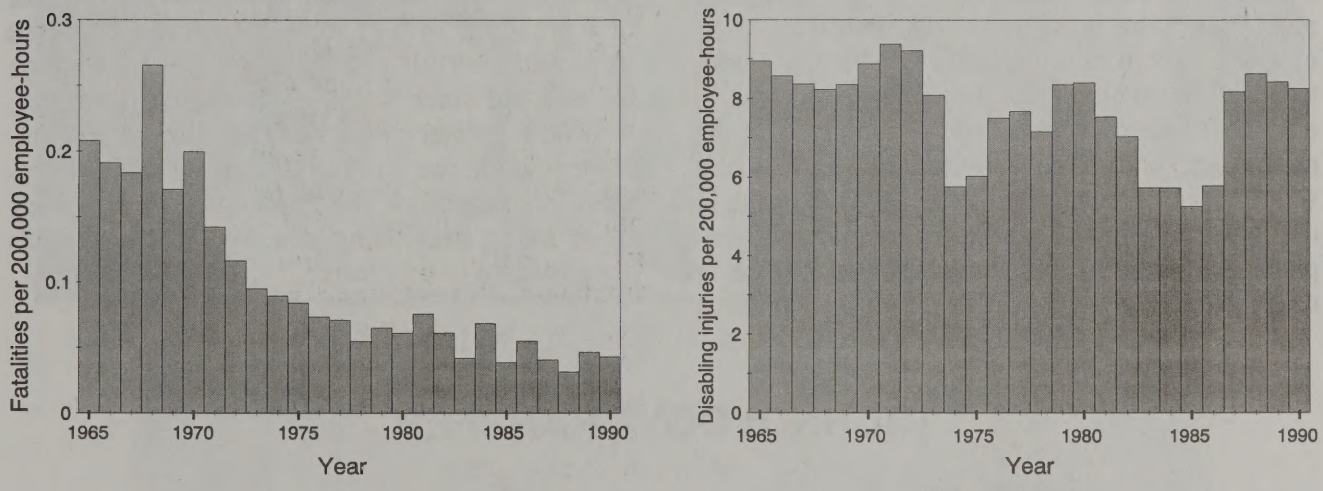


FIGURE 1. - Fatalities and disabling injuries in the coal mining industry, 1965-90.

PROGRAM DIRECTIONS

In the health area, the principal emphasis has been on reducing respirable dust exposure, and significant progress has been made. However, the sixfold increase in productivity for many underground and surface coal mining operations has made compliance with the Federal dust standard of 2.0 milligrams per cubic meter (mg/m^3) difficult in some cases despite notable technological improvements in dust control. Similarly, noise and induced hearing loss continue to pose a problem within the industry. However, technology for reducing prevalent

noise sources has matured significantly under this research program.

The current interest in and concerns about the possible health effects of diesel exhaust have sparked considerable regulatory, as well as research, activities. Bureau scientists have made notable progress in the control of emissions from diesel-powered mine vehicles, especially the reduction of particulate emissions.

Research in the safety area has encompassed many programs, including ground control, human factors, and fire and explosion prevention. While progress has been made, MSHA has established a goal of zero fatalities by the year 2000. Bureau research on improved technology is expected to contribute toward realization of that goal.

The emphasis and selective accomplishments of each research area are briefly summarized in subsequent sections of this publication. The funding to accomplish these improvements has varied based on total available funding and prioritized needs within the various program areas. Despite declining resources, progress continues to be made in many important areas.

PROGRAMMATIC CHANGES

The Bureau's health and safety program has experienced significant changes since the passage of the 1969 Act. Early in the program, much emphasis was placed on retrofit technology to assist in compliance with the new statutory requirements of the Act. The need was to ensure that there were means to comply with the new health and safety requirements and to find ways to accomplish the directives provided in the legislation. As a result, there was more emphasis on shorter-term, "quick fix" solutions to many problems. Also, the program placed much importance on equipment-oriented efforts. The program has now evolved to where many studies are of a longer-term nature, searching for new solutions to problems as opposed to means to provide retrofit and stopgap fixes. Although the new approach is longer-term and higher-risk, it offers greater rewards over the long haul. Hence, while the number of individual contributions coming from the Bureau's program may seem to be decreasing somewhat, the rewards are expected to be greater.

TECHNOLOGY TRANSFER

The Bureau's health and safety program is directed toward the development and assessment of improved technology. Since the Bureau is not in the business of producing devices for commercial use, this technology must be "transferred" to others who will apply it and produce such equipment. This is, in essence, the role of the Bureau's "technology transfer" program.

The effectiveness of the Bureau's health and safety program is measured in part by the extent to which technological advances are translated into practical applications. Such technology transfer has always been viewed as a vital and culminating element of the overall research process. Technology transfer tools at the Bureau's disposal have included special publications, films, seminars, workshops, exhibits, cost-sharing research agreements, and liaison with the mining, labor, manufacturing, and marketing sectors to inform the mining community and the public of research achievements (fig. 2). This activity received significant reinforcement with the passage of the Federal Technology Transfer Act of 1986. The act provides improved mechanisms for licensing of new technology to the private sector, encouragement and better means to enter into cost-sharing agreements with the private sector, and better access of private sector organizations and individuals to Federal laboratories and their unique equipment.

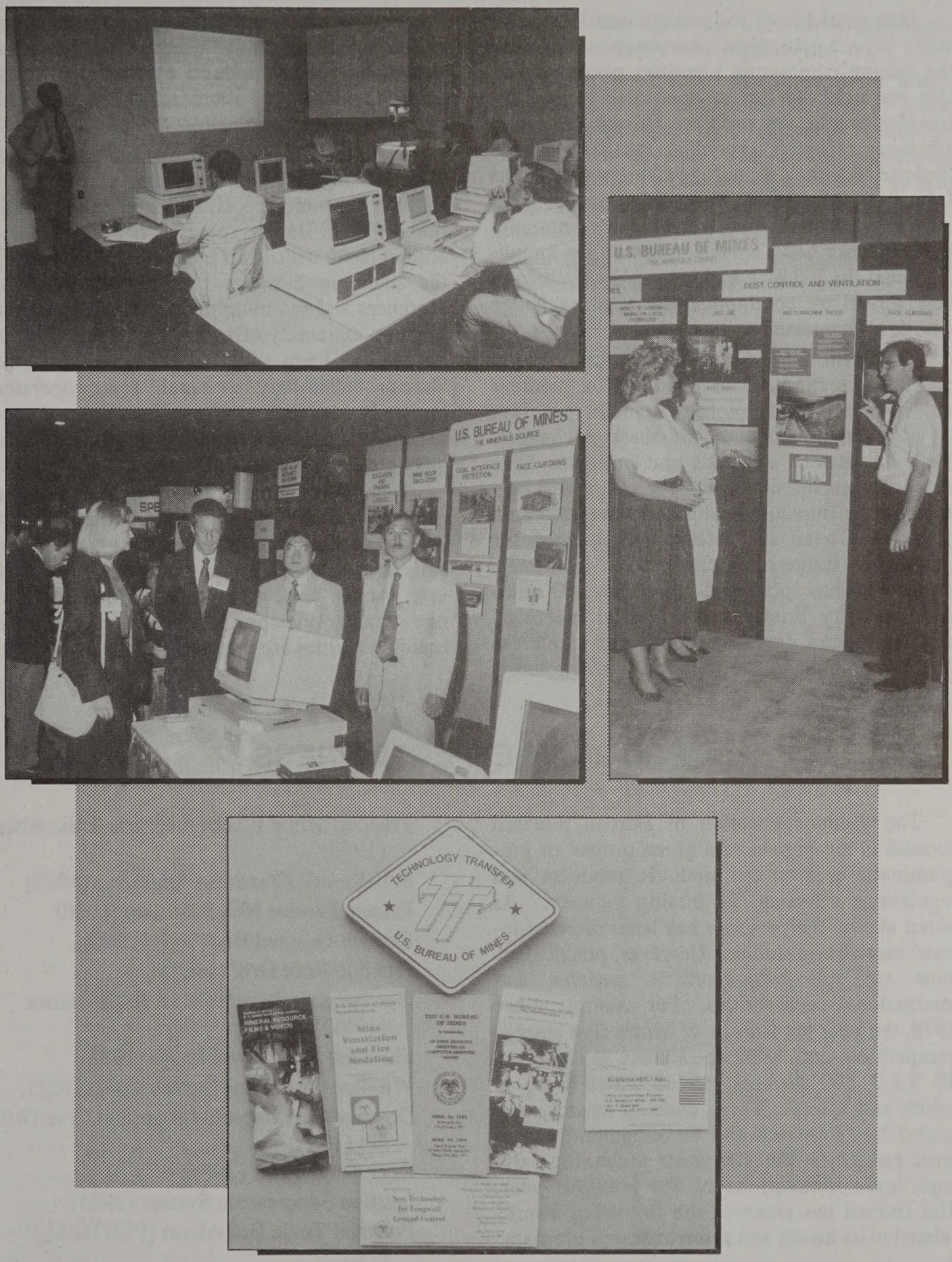


FIGURE 2. - Seminars, workshops, exhibits, and special publications have proved to be powerful technology transfer tools for the U.S. Bureau of Mines.

Bureau of Mines technology transfer has always been a reciprocal phenomenon in which the mining community identifies needs for further research. At Bureau-sponsored technology transfer events, not only are Bureau-sponsored advances reported, including results from the Generic Mineral Technology Centers, but results from foreign research laboratories, independent university studies, and the mining community are also described. This is done with the knowledge that the industry and indeed the Nation are best served by continuous and vital exchange among all interested parties.

In addition to disseminating information on recent technological advances, a primary objective of the technology transfer program is to maintain a forum for these exchanges. Such discussions of needs and problems have helped to establish the proper focus and balance of the Bureau's health and safety research program. These are essential exchanges for identifying future research thrusts. Since 1972, the Bureau has sponsored more than 300 seminars, industry briefings and special meetings, workshops and demonstrations, and major exhibits pertaining to the program. Additionally, the Bureau has evaluated satellite broadcasting to provide more timely and effective dissemination of research ideas and exchange of information with viewers in the geographically dispersed minerals industry.

Experience has shown that one of the most effective means of transferring technology is through in-mine experiments and demonstrations. When Bureau researchers visit a mine to collect basic data or to evaluate a new concept, the dialogue between the state-of-the-art researchers and the mine management has proved to be an extremely efficient tool. Particular emphasis has been directed toward transferring Bureau technology to small mine operators. Specially prepared reports and seminars that address their particular needs, such as dust control, have proved to be very effective.

Technology transfer is an integral part of all research activities, beginning with the individual project conception and continuing until the results are successfully introduced for industrial use. Active review of projects from a technology transfer viewpoint is made to ensure research activities are meeting real needs.

PROGRAM EFFECTIVENESS

The ultimate criterion of Bureau research success is the impact of a given project or programmatic area on the methods, products, and regulations affecting the mining industry. As noted above, the program has been directed toward more basic studies. However, practical results are still recognized in national and international competitions. For example, since 1978, the year the Bureau of Mines first entered competition, until 1992, the Bureau has received 30 R&D 100 Awards, 15 of which were in health and safety. These coveted awards, presented by "Research and Development" magazine, recognize the 100 most technologically significant innovations of the previous year. The Bureau has received the following awards related to its health and safety research program:

Model Fibrous Aerosol Monitor (1978)
Reusable Ventilation Control Stopping for Underground Mines (1978)
Trapped Miner Electromagnetic Transmitter (1979)
Self-Rescue Breathing Apparatus (1980)
Palmes Passive NO_x Samplers (1980)
Cement Grouted Roof Bolt (1980)
Flexible Roof Drill (1981)
Geodynamic Accumulated Strain Sensor (1981)
Sheathed Explosive Charge (1982)
Wireless Real-Time Survey Tool (1982)
Downhole Replaceable Diamond Core Drill Bit (1982)
Rock Dust Meter (1985)
Ignition Suppression System (1985)
Personal Toxic Gas Alarm (PERTGAL) (1989)
SR-100 Ultra-Lightweight Rebreather (1991)

This publication focuses on the achievements of the Bureau's health and safety program since the passage of the 1969 Act. Notable progress has been made in all areas, but the major accomplishments may be categorized as (1) acquisition of data and identification of techniques as the basis for new standards and/or modification of an existing standard, (2) identification of suitable compliance technology for existing and proposed standards, and (3) identification of more cost-effective means to comply with regulations.

Much work has been done, with notable successes in the traditional "hardware" aspects (rock mechanics, roof supports, ventilation, etc.). There have also been notable accomplishments in the "software" aspects, such as training, biomechanics, human factors, and organizational development. Following are highlights of Bureau of Mines accomplishments in all aspects of its health and safety program.

RESPIRABLE DUST

Following passage of the Federal Coal Mine Health and Safety Act of 1969, the Bureau of Mines initiated a research program aimed at controlling respirable dust exposure of coal mineworkers. As used here, the term "respirable dust" refers to the coal mine dust that gets into and interacts with the lungs of those who inhale it. It has only recently been recognized as a severe hazard to mineworkers in the United States. This program has been implemented by a team effort consisting of the Bureau's in-house capabilities, the Generic Mineral Technology Center for Respirable Dust, and contractors. Over the years, Bureau research has addressed three principal areas:

- Near-term assistance to meet the Federal 2.0 mg/m^3 dust standard by suppressing, collecting, and/or diluting dust generated and entrained;
- Long-term, high-risk engineering design changes to the cutting system to reduce the dust produced;
- Improving dust measurement techniques and sampling equipment.

Additionally, fundamental studies have been conducted by the Generic Mineral Technology Center for Respirable Dust, with emphasis on penetration of dust into the lungs. Accomplishments have been significant, but problems remain, as noted below.

THE NEW 2.0 mg/m^3 DUST STANDARD

The 1969 Act established a 2.0 mg/m^3 dust standard for all coal mining operations, underground as well as surface. At the time of enactment of this legislation, the industry was averaging approximately 4.0 mg/m^3. The Bureau's respirable dust research program played a significant role in identifying and developing effective technology to allow better compliance with this new standard, aided by industry implementation and Federal enforcement.

Improved Dust Sampling Methods and Devices

Coal mine dust personal sampling units (CMDPSU) traditionally have been used for compliance measurements (30 CFR 70, 71, and 90) and to collect exposure data for epidemiological studies. These gravimetric devices are well suited for determining compliance since the standard is based on mass concentration measurements collected during entire working shifts. They serve well for epidemiological studies when worn by the worker to obtain personal exposure measurements. However, they are often too slow and labor-intensive to be an effective engineering tool or to provide feedback on dust control systems.

During the past 2 decades, several improvements have been developed for the CMDPSU. In 1978, the Bureau sponsored the development of an improved, tamper-proof filter cassette. It prevents backflushing, has a protective trap feature to help prevent shaking dust from the filter, and incorporates a total air volume indicator to signal partial shift sampling. The Bureau was also instrumental in the development of sampling pumps that automatically controlled the airflow rate to 2 liters per minute despite increased back pressure caused by filter loading.

Since 1978, the Bureau has developed several dust monitors that, depending on their intended application, can have distinct advantages. GCA Corp. designed and fabricated a prototype respirable dust monitor for the Bureau in 1978 based on light-scattering techniques. The instrument, known as the RAM-1, is now being manufactured by MIE, Inc., Bedford, MA. The RAM-1 is a portable, fully self-contained nephelometer that measures and displays instantaneous respirable dust levels in the air. MSHA has approved it for use in explosive methane-air atmospheres.

In 1982, the Bureau contracted Rupprecht and Patashnick Co. of Albany, NY, to design

and fabricate a prototype device called the tapered-element oscillating-microbalance (TEOM) (fig. 3). The TEOM does not use light scattering, but measures the change in oscillating frequency of a filter mounted upon a glasslike pedestal and relates that change to the mass of dust collected on the filter. The device as delivered to the Bureau is not commercially available, but Rupprecht and Patashnick Co. has manufactured other devices using the TEOM dust-sensing technique for other applications.

GCA Corp. designed and fabricated a new-generation nephelometer for the Bureau in 1983. Known as the MINIRAM, it was designed as a passive device and requires no sampling pump (fig. 4). The MINIRAM displays the current dust level reading, a time-weighted average, an 8-hour equivalent shift average, or the sampling time. It also stores up to seven average dust level readings for playback over the display or for digital output to a printer or computer. The MINIRAM is also commercially available from MIE, Inc., and has been approved by MSHA for use in explosive methane-air atmospheres.

The quartz content of dust is an important consideration when assessing potential health hazards. In 1983, a Bureau- and NIOSH-sponsored comparison of x-ray and infrared quartz analysis methods showed them to be unbiased, giving similar results for coal mine samples. The study showed that the easier-to-use infrared technique was sufficiently rugged, measuring within 25% of the "true" value 95% of the time.

Over the last 2 decades, a variety of dust measurement technologies and mineral content analysis techniques have been and continue to be investigated. As discussed, some are commercially available, while others were developed only to the prototype stage to prove the measurement principle. The CMDPSU continues to be a reliable device to measure average concentrations of airborne respirable dusts, especially for compliance purposes. Nephelometers offer mechanical simplicity and instantaneous reading of dust levels, but do not measure mass concentration. Changes in particle characteristics (size, shape, and index of refraction) of the dust cloud can introduce error and require calibration for each dust type. These characteristics of nephelometers make them desirable for evaluating dust controls and performing dust surveys, but require additional work if used for compliance monitoring. Each technique can be judged only with respect to a given application.

Ongoing Bureau research strives to improve the performance of nephelometers by helping them to distinguish between coal mine dust particles and water droplets. Sophisticated Fourier transform infrared (FTIR) techniques promise to improve measurement sensitivity for quartz and simplify analysis procedures by allowing direct, on-filter analysis.

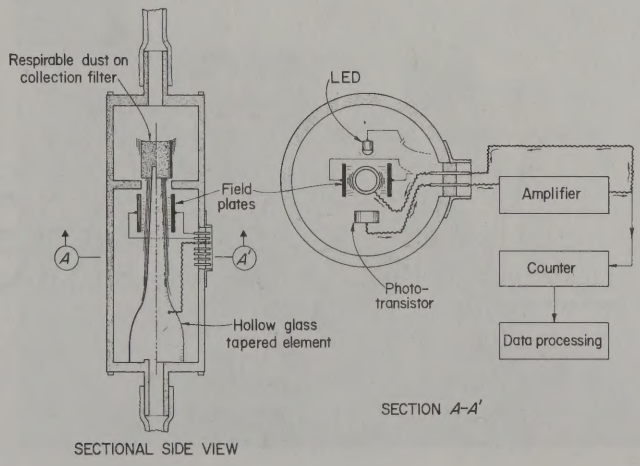


FIGURE 3. - Tapered element oscillating microbalance (TEOM).

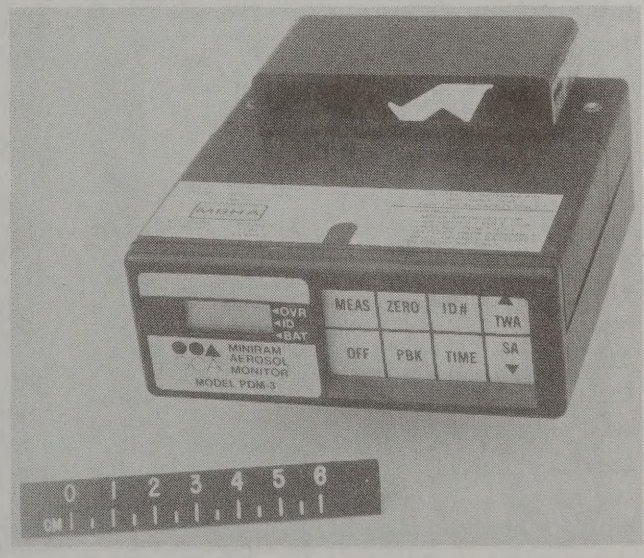


FIGURE 4. - The MINIRAM—a personal dust monitor.

Design and Development of an In-Seam Tester

To limit personal respirable dust exposure, more extensive knowledge was required of the characteristics of different coal seams as they relate to the generation of respirable dust. To address this need, the Bureau developed an in-seam tester (fig. 5), which has provided valuable data on the cuttability and friability of different coals. These data cannot be obtained in a laboratory because of the fracture and cleat structure found in most coal seams. Using this device in the actual underground mine environment has yielded valuable information that has led to alternative cutting techniques and new designs for cutting heads. Data acquired with the in-seam tester can be used to tailor the cutting system to the specific physical characteristics of individual mining operations.

Improved Water Spray Systems

One of the most widely used and effective dust control techniques is the application of sprayed water. However, the establishment and maintenance of satisfactory water sprays proved difficult in the conditions encountered in operating mines. Principal problems related to the need for fine atomization and the clogging of water spray nozzles by rust scale and other contaminants typically found in an industrial water supply. Bureau research has found a method that maintains water sprays in effective operating condition. This filtration system, which uses commercially available components, is a cost-effective assembly now employed extensively throughout the industry to prevent nozzle clogging.

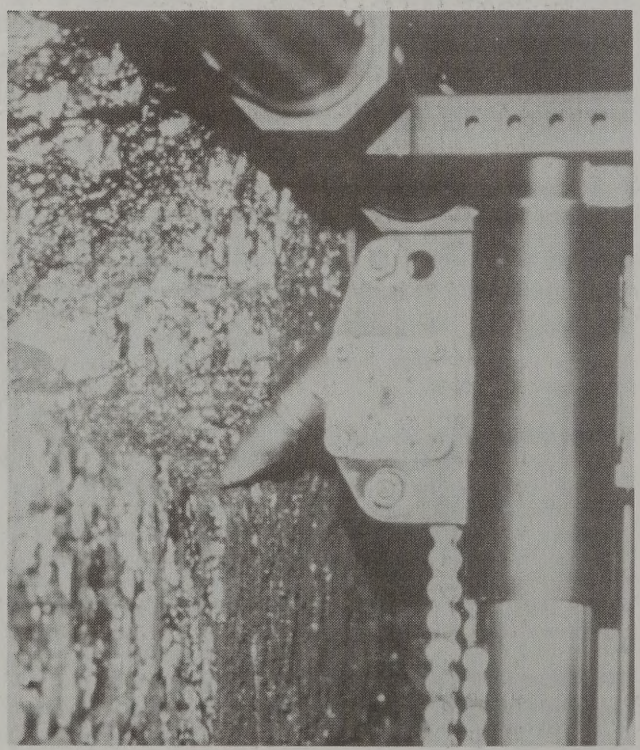


FIGURE 5. - Bureau-developed in-seam tester, which gives data on the cuttability of different coals.

Wet-Augers

Respirable dust control on Wilcox and Jeffrey auger miners has been one of the most difficult dust problems facing the underground coal industry. The Bureau developed and tested a new method of dust control called the wet-auger system (fig. 6), whereby water is transferred through rotary water seals into the auger shaft and then to water spray nozzles located on the augers. This system reduced dust levels 50% compared with the conventional fixed sprays at equal water flow rates. All Wilcox and Jeffrey auger miners in the field in the early 1970's were converted to wet-augers. Since 1975, all Wilcox and other auger miners manufactured by Fairchild Equipment Co., the only remaining manufacturer of auger miners, have been built with wet-augers as standard equipment.

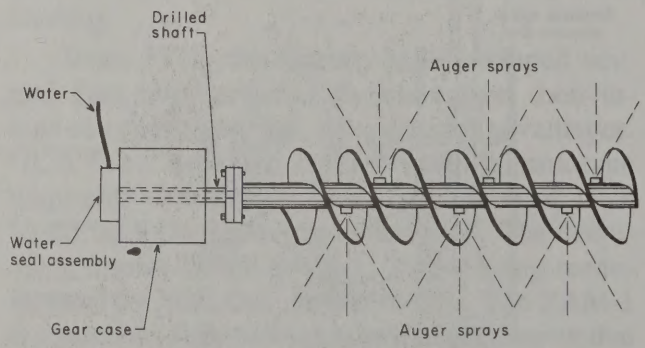


FIGURE 6. - Wet-auger system for dust control.

Improved Personal Protection

In addition to controlling the amount of dust generated and the amount of dust that becomes airborne, Bureau research has addressed alternative techniques to protect the individual miner. Under certain conditions, an airstream helmet (fig. 7) is effective in reducing the amount of inspired respirable dust. This device is now used extensively in some mining operations, such as at longwall faces.

Dust Scrubber Systems

While the concept of scrubbers to clean dust-laden air underground was attractive from the early days of the program, there were numerous obstacles to overcome before scrubbers could be utilized successfully in operating mines. The first problem was scrubber efficiency for the fine coal particles (less than 10 micrometers) present in respirable dust. The Bureau-developed flooded-bed scrubber has proved to be an effective tool in this regard, with collection efficiency for respirable dust exceeding 95%. Additionally, there were some significant engineering problems involved in integrating scrubbers into equipment such as the continuous miner. However, working in close cooperation with the equipment manufacturers, such integration has been successfully accomplished. At this time, more than 350 such installations are in use in the United States.

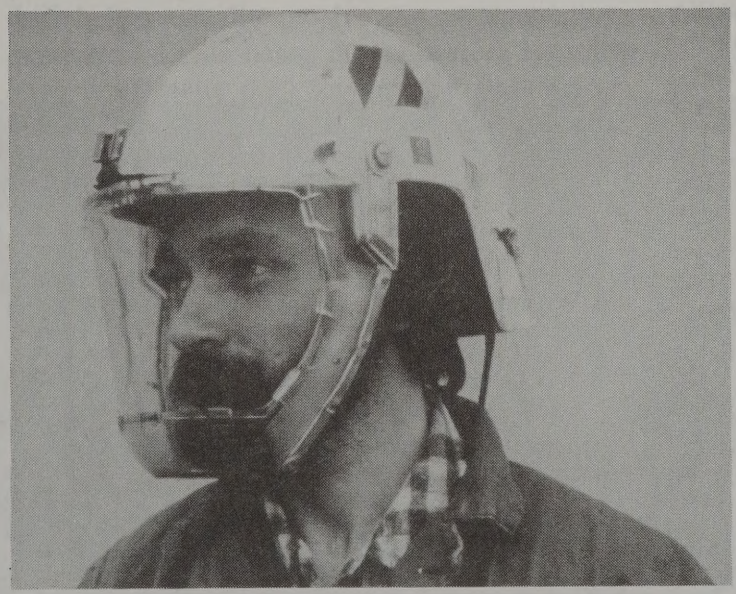


FIGURE 7. - Airstream helmet, an alternative method to provide reduced dust exposure.

Accomplishments

Owing to Bureau research, the cooperation of the industry, and work by other Federal and State agencies, average dust exposure on continuous miner sections is now below 2.0 mg/m^3. Due to new concerns raised by quartz dust found in respirable dust samples, additional problems are now being addressed, as discussed later.

DUST CONTROL FOR LONGWALL MINING

The second major thrust of Bureau research has been toward longwall mines. In 1976, more than 70% of the longwall shearer faces in the United States were consistently out of compliance. Through an aggressive program, the Bureau has been able to identify alternative technologies to control respirable dust exposure on longwall faces.

Shearer Clearer Water Spray System

Water sprays have been used extensively by mining companies to control respirable dust. A typical water spray captures about 25% of the respirable dust that becomes airborne, while the remaining dust is moved about by the air-moving action of the water sprays and boils out over the shearer operator. In actual mining situations, the exposure of the shearer operator can be increased by as much as 50% owing to this air-moving action. Bureau research has shown that by reorienting the existing water sprays, their air-moving capability can be effectively utilized to reduce dust exposure. Reoriented water sprays are used to divert the dust-laden air toward the face and away from the shearer operator. The shearer clearer concept lowers shearer operator dust exposure by an average of 50%. Today, more than 80% of longwall shearers in the United States utilize the shearer clearer system, and the concept has been exported to Canada and Australia.

Improved Localized Ventilation Control

Uncontrolled loss and misapplication of face ventilation can significantly affect the respirable dust exposure of longwall face personnel. Examples include the amount of air leaking into the gob or waste behind the longwall supports in the headgate, as well as how the airflow is directed over the shearer cutting drums when the shearer reaches the headgate. Bureau studies have shown that gob curtains can improve average face airflow by more than 30% and can significantly increase airflow along the entire face. Almost all U.S. longwalls now use gob curtains to manage the primary airflow more effectively and reduce face workers' respirable dust exposure.

Modified Cutting Sequence

Currently, more than 50% of double-drum shearers in operation in the United States employ a unidirectional cutting sequence. Typically, the primary cut is taken in the same direction as the face ventilation. The primary source of the shearer operators' dust exposure is dust from the upwind drum spreading out into the walkway, increasing respirable dust exposure of both operators. If the upwind drum is raised and the trailing drum is used to cut the remaining bottom coal during the cleanup pass (modified unidirectional cutting), both operators can work on the intake (clean) air side of the primary dust-generating source, significantly reducing their exposure to dust generated during cutting. While unidirectional cutting may affect overall productivity, it has been shown to be an effective tool in helping to maintain compliance with dust regulations.

Deep Cutting To Reduce Dust Generation

With deep cutting, larger fragments of coal are removed and fewer coal surfaces are exposed, resulting in less airborne dust. Extensive evaluation of deep-cutting shearers has clearly shown that doubling the depth of the cut can reduce airborne dust levels by as much as 60%. While there are some limitations in terms of implementing this technique on existing shearers, with new equipment and/or appropriate modification of existing equipment this has proved to be an effective and well-utilized means to promote dust compliance.

New Cutting Concept

The Bureau has developed an entirely new cutting concept to reduce dust generation at the source. Those elements of rotary drum cutting systems that research has identified as having a significantly negative impact on the generation of respirable dust and fines include: constantly varying depths of cut, no dynamic interaction between bits in the coal, secondary dust generation by grinding of already fragmented coal, entrainment of dust generated and frictional heating of bits due to high drum revolutions per minute, and excessive bit wear due to frictional heating. These problems, inherent in the design of rotary drum mining machines, can be controlled by changing from rotary to linear cutting drums (fig. 8). The Bureau has identified linear cutting as an advanced technology for longwall and continuous mining machines. A linear drum cuts easily and smoothly, with a minimum of dust and fines, and at a bit speed slow enough to keep bit temperatures low so that ignitions and accelerated bit wear are minimized.

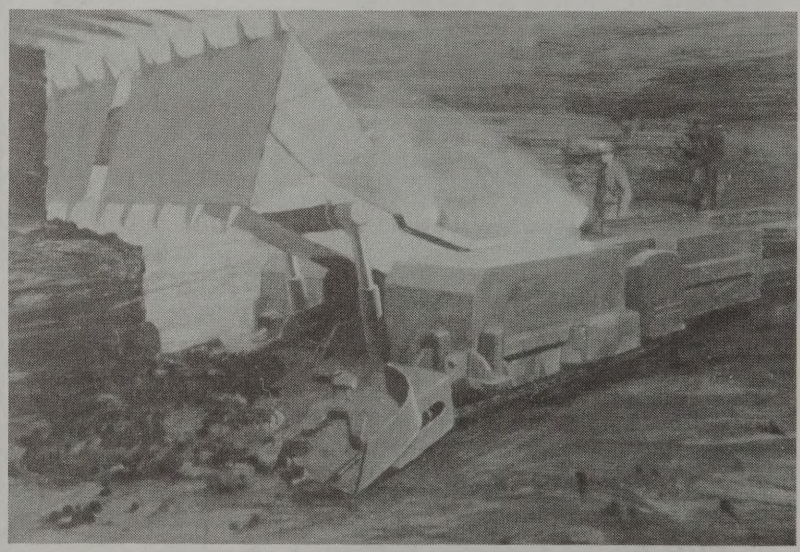


FIGURE 8. - Artist's concept of a constant depth linear cutting head continuous miner.

Control of Dust Generation During Coal Transport

Assuring a supply of clean intake air to the longwall face area is critical in minimizing face workers' dust exposure. On most longwall operations this is difficult to achieve because of dust generated by the coal crusher and at transfer points outbye the face (located in the intake). The Bureau has demonstrated that by enclosing the stageloader/crusher unit and installing water sprays at strategic locations along the unit, the intake dust levels can be reduced by as much as 60% (fig. 9).

Accomplishments

Respirable dust levels on longwall faces in 1976 averaged approximately 6.8 mg/m^3. Through combined efforts of the Bureau, mine operators, and MSHA, the average dust level in 1983 was reduced to approximately 2.0 mg/m^3. Compliance levels have risen from 30% in 1976 to 85% in 1986. However, increased output on longwall faces continues to make compliance a difficult problem. Work is underway to identify future research needs in this area.

DUST CONTROL FOR SURFACE MINES

According to MSHA data, the driller and drill helper usually receive the greatest quartz exposure. Drills using dry collectors typically have three major dust sources that significantly reduce the overall effectiveness of the collector: (1) the dust collector dump cycle, (2) drill shroud leakage, and (3) leakage around the drill stem seal in the drill table. Of these, the most significant is usually the collector dump cycle. It can account for 40% of the respirable dust emissions. The Bureau has investigated new concepts to improve the overall effectiveness of dry collection systems, wet drilling, and dust control.

Optimization of Wet Drilling

Wet drilling can suppress respirable dust by as much as 97%. However, the amount of water used is critical for both dust control and satisfactory drilling performance. As a result of Bureau tests, a very practical, simple, operational guideline can be provided to all mine operators performing wet drilling that automatically accounts for various operating conditions such as different drills, changes in bit size, and different strata. To operate at close to the optimum water flow rate, the operator should slowly increase the amount of water just to the point where visible dust emissions are abated. Due to the initial sharp increase of dust control effectiveness, the visible dust abatement point will be easy to identify. Addition of more water beyond this point will not provide any significant improvement in dust control, but will most likely create operational problems. It is important that the water be increased slowly to account for the lag time as the air/water/dust mixture travels from the bottom to the top of the hole.

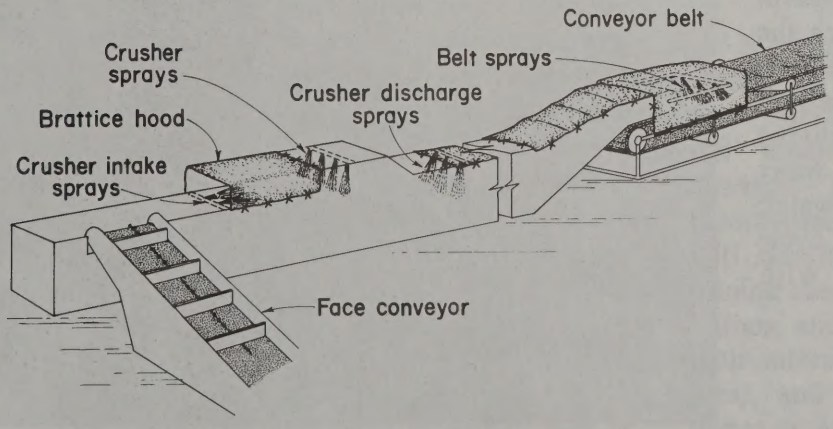


FIGURE 9. - Modified stageloader/crusher reduces dust on longwall face.

Air Ring Seal for Dust Suppression

The Bureau of Mines has successfully field-tested a low-maintenance, nonmechanical seal at a surface coal mine in Missouri to reduce dust emissions arising from the gap between the drill pipe and deck bushing. The drill pipe leakage is important because it is in the immediate vicinity of the drill cab. Since many drills have cabs that have lost their dust-tight configuration, this dust source represents an immediate hazard to the driller. The seal is a

doughnut-shaped compressed air manifold with closely spaced holes along its inside perimeter and is designed for installation on the underside of the drill deck. When compressed air is supplied to the manifold, high-velocity air jets are produced through the holes. These high-velocity air jets are directed across the opening to be sealed to impede movement of dust particles through the opening. In a hole-by-hole comparison at the mine, the air ring seal initially reduced respirable dust levels between 41% and 70%, with an average of 55%. After improving the installation arrangement, performance improved significantly, with all visible cuttings and dust eliminated from the abovedeck area. After more than a year, the mine was still using the device successfully and has fabricated additional air ring seals for its other drills.

Dust Agglomerator

As mentioned earlier, the dust collector dump cycle is usually the most significant dust source, accounting for 40% of the respirable dust emissions. Bureau researchers believed that some type of dust agglomerator would eliminate this dust hazard. The pin-type agglomerator used is a horizontal, stationary-shell, cylindrical agitation pelletizer with a horizontal shaft. The pins mounted on the shaft are oriented in a helix. They rotate inside the shell, imparting a spinning motion to the dust particles in the vortex behind the pins. As they rotate, the particles become coated with a liquid binder (if used) and collide with other particles. As a result, they coalesce into dust-free micropellets. The helical pin arrangement conveys the material axially through the machine to the end of the shell. There it drops out as nonuniformly-sized pellets. A screw conveyor meters the dust into the pelletizer, and at intervals a water spray system injects small amounts of water. Dust levels from the collector dump cycle were reduced from 65% to 73% with 0.1 gallons of water per minute.

Accomplishments

Bureau research on surface drill dust has resulted in several practical, low-cost methods for reducing operator exposure that are beginning to be implemented in the coal industry. Additional results are available that pertain to drill shroud capture efficiency, respirable dust transport, and water separation from the bailing air.

MORE STRINGENT RESPIRABLE DUST STANDARDS

The third major thrust of the Bureau's respirable dust program pertains to quartz dust control. Whenever the quartz content of respirable dust exceeds 5%, regulations require the 2.0 mg/m^3 dust standard to be reduced. Approximately 35% of the industry is now affected by the more stringent dust standards (below 2.0 mg/m^3). Two major sources of quartz dust in underground mining operations are the continuous miner, when cutting floor and roof rock or rock partings within the seam, and the roof bolting machine, while drilling the roof.

Half-Curtain Face Ventilation System

In sections with marginal intake air velocity, the half-curtain can be used to decrease the cross-sectional area of the mine entry and hence increase the intake velocity over the miner operator, helping to confine the dust to the face area. Figure 10 shows installation in an operating mine. With a half-curtain, dust is reduced at the continuous miner operator station by about 50% when intake air velocity is marginal.

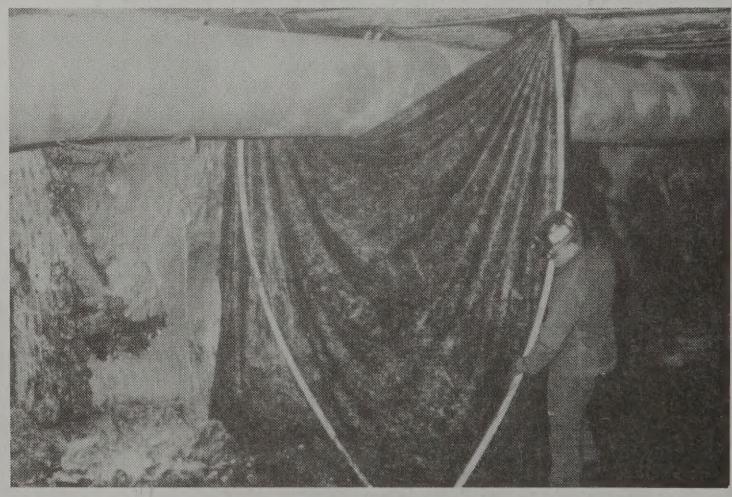


FIGURE 10. - Underground installation of half-curtain to increase air velocity over the miner operator.

Modified Cutting Sequence Reduces Quartz Dust Generation

One primary source of quartz dust is the continuous mining machine when cutting roof rock. A modified cutting sequence has been successfully implemented—the top coal/rock is undercut, then the coal/rock material near the roof is cut to a free face. This sequence, which generates less dust, also helps to confine the dust cloud under the machine where it can be effectively suppressed by the water sprays before it can enter into the main airstream. The modified cutting sequence has been shown to eliminate operator quartz dust exposure while reducing quartz dust levels in the return by as much as 65%.

Water Sprays for Improved Ventilation Control

One primary factor affecting the miner operator's dust exposure is dust rollback from the face. It is usually caused by low primary airflow and a poorly designed machine water spray system. Water sprays are effective air movers; depending on the specific circumstances, that movement of dust-laden air by water sprays may be advantageous. Water sprays that travel a long distance before impacting any solid surface are effective air movers, while water sprays that travel only a short distance before impacting the cutterhead or another part of the machine are more effective in suppressing dust and do not exhibit the air movement features. When the sprays do move the dust-laden air, dust tends to roll back toward the continuous miner operator. Marginal air velocity from the principal air system will cause the localized air movement induced by the water sprays to overpower the primary ventilation system. The Bureau's antirollback system and guidelines for its installation have been effective in reducing machine operator dust exposure by as much as 40%.

Control of Quartz Dust During Roof Bolting

The second major source of quartz dust is the roof bolting machine, when drilling into roof rock. The Bureau has evaluated various bit types available to the industry and found a 5:1 difference in the amount of airborne dust generated by different types. Based on Bureau studies, most manufacturers and mining companies have now adopted the dust hog bit, an effective and proven antidust design. Other Bureau studies have shown that maintenance, especially of the dust collector system, on roof bolters is critical for proper dust control. According to an independent study by MSHA, 90% of the sections surveyed have achieved compliance by implementing the Bureau's recommendations.

Scrubbers for Improved Quartz Dust Control

Although 90% effective for removing respirable coal dust, the conventional flooded-bed scrubbers, described earlier, are less than 50% effective in removing quartz dust particles, which are typically one-tenth the diameter of respirable dust particles. This means that the quartz dust collection efficiency of flooded-bed scrubbers is unacceptable. The Bureau has investigated methods to correct this. Studies indicate that random-weave, synthetic collection bed media can increase the quartz collection efficiency to 97%. The Bureau has also identified and tested a high-pressure water-powered scrubber for continuous mining machines. Initial results indicate that the system can improve quartz dust removal by approximately 40%, compared with flooded-bed units. Additional field evaluation is underway.

Cutting System Modeling

Mine operators have been provided with the means for evaluating dust generation and bit wear effects on increased coal production without making costly trial-and-error machine changes. The Bureau has developed microprocessor-based iterative computer programs that will simultaneously evaluate any given set of mining machine parameters, specific seam conditions, and operator controllable parameters for their interactive effects on dust generation, bit wear, and production by either a continuous miner or longwall shearer. The programs provide relative dust, cutting forces, and production values.

Expert Systems for Respirable Dust Control

While progress has been made in dealing with the more stringent dust standards, additional work now underway offers significant promise of further improvements. The Bureau has developed expert systems for both continuous and longwall mining. Expert systems provide guidance to the mine operator in all areas of respirable dust control from water sprays and machine design to ventilation concepts. They are operated on desktop computers. Preliminary field evaluation has been encouraging, and further expansion of this technology is anticipated. This will enhance the accuracy and rapidity of Bureau technology transfer.

Water and Air Guidelines for Dust Control

Laboratory tests were conducted to determine the respirable dust reduction effectiveness of and interaction between face airflow and water sprays when applied at various operating levels on a continuous miner. Testing was conducted in a full-scale model mine entry where air and water application could be easily monitored and controlled. Exhausting face ventilation was varied from 3,000 to 9,000 cubic feet per minute (cfm), miner spray-waterflow was varied from 15 to 35 gallons per minute (gpm), and nozzle operating pressure was varied from 80 to 200 pounds per square inch (psi).

Interactions between dust control parameters were found to be significant and often defined the level of application for a control parameter at which further increases in that control parameter did not produce continued reductions in dust concentrations. Regression modeling indicated that increases in airflow to 8,400 cfm, waterflow to 25 gpm, and water pressure to 140 psi could typically be used with beneficial results.

Accomplishments

More than 35% of underground mining operations are currently under more stringent (below 2.0 mg/m^3) dust standards. Whereas in 1983 fewer than 20% were able to comply with these reduced standards, today more than 50% of sections are able to operate at these levels. Through Bureau research and industry implementation, quartz dust generation during roof bolting has been almost eliminated. A fundamental, as well as practical, understanding of quartz dust generation and behavior has been achieved. With continued efforts by the Bureau, mine operators, and MSHA, further improvements in this area are expected.

ONGOING RESEARCH

Coal wettability is being studied by the Bureau for its fundamental mechanisms and its relation to the surface chemistry of coal, with the ultimate goal of developing consistently effective dust suppression reagents that can be added to the conventional water spray systems. Underground testing has demonstrated that the reagent addition improved dust reductions by more than 60%, compared with water alone, when added to the water spray system of a continuous mining machine.

The Bureau has researched and optimized several techniques to reduce workers' respirable dust exposure in mineral processing plants. The focus has been on those areas and jobs where workers are exposed to the highest dust concentrations. Both the National Industrial Sand Association and MSHA consider these to be the bag loading and bag stacking operations. A number of different dust control systems have been developed by the Bureau for these areas. The dual nozzle system reduces the bag operator's dust exposure by 83%. Packing Equipment Specialist, a company in Tustin, CA, is seeking to commercially manufacture this system on all new bag filling machines. Another system developed by the Bureau is the Overhead Air Supply Island. This device provides an envelope of clean air for dust protection for individuals at work stations, such as the bag operators, when other engineering controls are not practical or available. This system reduced a bag operator's respirable dust exposure by 98% at one silica sand operation. For the bag stacking operation, the Bureau has also developed a number of effective techniques. One is the pallet loading dust control system (fig. 11), which uses a push-pull ventilation system to sweep the dust generated during the stacking process away from workers into an exhaust ventilation system. This technique reduced workers' dust exposures

FIGURE 11. - A Bureau-developed pallet loading dust control system can reduce bag stacker dust exposure by about 70%.

about 70% and also improved the bag stacking process from an ergonomic standpoint, reducing back fatigue and injuries in this job function. When bags of product are transported and stacked directly into railcars or trailer trucks by using a snake conveyor, the Bureau has shown that a 2,000-cfm exhaust ventilation system could reduce dust levels between 65% to 95% inside these vehicles.

FUTURE PROBLEM AREAS

The problem of more stringent dust standards is expected to grow. The formula for determining reduced standards is:

$$\text{Dust standard} = \frac{10}{\text{percent quartz}}$$

Based on this standard, the formula for more stringent standards has required many mining companies to operate at or below 0.8 mg/m^3. To date, approximately one-third of the coal mining industry has been placed on more stringent dust standards due to quartz. Control techniques must be improved if mandated levels are to be reached.

As longwall production increases, dust levels will also increase. Average longwall production by the end of the 1980's was 1,900 tons per shift with an average dust level of 2 mg/m^3. In 1991, this average longwall production was 2,500 tons per shift. However, much of the current successful compliance with respirable dust has had an adverse effect on productivity. In light of the industry trend toward increased longwall production, new control technology must be developed to maintain compliance with the Federal dust standard.

Only through a more basic understanding of the sources and methods of dust generation can the current level of control technology be advanced to adequately address the longwall dust problem. Research under this program will concentrate on obtaining an elemental analysis of dust generation mechanisms from stageloader/crusher operations, conveyor belt and ventilation systems, face sloughage, and airborne respirable quartz. Efforts will then utilize these findings to identify and evaluate state-of-the-art dust control technology required on high-production longwall faces.

The development of a total longwall dust simulator should prove invaluable from the standpoint of both a research tool and an application tool for the longwall mining industry. A computer simulator that could predict what impact productivity or panel design changes would have on ambient dust levels, along with estimating the impact of changes in dust control implementation, would allow research to

concentrate its limited resources in the most critical areas, while allowing the industry to estimate changes in dust levels as a result of operational changes from a health and safety standpoint. This may enable a total systems approach to control of longwall dust through an expanded data base for estimating dust levels and control procedures.

Silica dust control research will focus on technologies that enhance suppression efficiency of smaller-sized silica dust, improve the energy efficiency of two-phase fluid transfer systems, investigate preconditioning seam processes applied before mining, study air curtain concepts, and examine potential silica dust problems in metal and nonmetal mines. Research on increasing the efficiency of water application will be directed toward investigating technologies that increase the probability of water capture and/or agglomeration of smaller-sized silica particles. This will encompass studying several alternative technologies to generate smaller water droplets and the effect of water droplet size on silica capture efficiency. Other water application technology will focus on intensifying momentum transfer induction systems. This work will involve vector analysis of water and air systems to amplify the constructive transfer of kinetic energy between the two fluids. Mechanisms to stimulate fluid flow through coal seams (permeability) will also be studied to provide effective fluid preconditioning processes of coal seams for airborne dust prevention. Fundamental coanda effects of air movement will be explored to identify potential localized ventilation applications for worker protection. Coanda tubes are devices that convert a supply of air from a fan onto a discrete curtain of moving air that can be directed and controlled. The coanda curtain uses an air expulsion slot to discharge a virtually straight flow of air along one guide surface. After emerging from the slot, the jet of air follows the line of the guide surface, then slowly expands by collecting the surrounding air. Lastly, sources and concentrations of silica dust in underground metal and nonmetal mines will be assessed to project the anticipated impact of the new dust regulations on this industry.

Bureau studies have identified the nature of airborne particulate generated by diesel engines. There is a significant difference in the size of respirable coal dust and that of diesel exhaust particulate. Ongoing Bureau studies are addressing means to more exactly characterize the chemical nature of these particulates and to prevent them from becoming airborne.

A detailed research evaluation of each of these concepts is needed to determine their potential benefits and to understand the basic theory of operation and potential application.

GENERIC MINERAL TECHNOLOGY CENTER FOR RESPIRABLE DUST

The Generic Mineral Technology Center for Respirable Dust was established in August 1983 at the request of the Bureau of Mines to conduct fundamental research that affords "...each miner the opportunity to work underground during the period of (his/her) adult working life without incurring any disability from pneumoconiosis or any other occupational disease." The Center consists of the Mining and Mineral Resources Research Institutes (MRI's) of The Pennsylvania State University and West Virginia University, in association with the MRI's of the Massachusetts Institute of Technology, Michigan Technological University, and the University of Minnesota. The Center brings together experts concerned with particles causing potentially disabling or fatal diseases, including pneumoconiosis ("black lung"), silicosis, and asbestosis, the last of which deeply concerns not only workers in the mineral sector but also the general public. The primary goal of the Center is to control respirable dust disease through a better understanding of the respirable dust generated by mining and milling and its interaction with the lungs. The Center's work concentrates on: (1) the dust-lung interaction; (2) dust particles characterization; (3) the relationship of mine environment, geology, and seam to dust generation and mobility; (4) the dilution, dispersion, and collection of dust in mine airways; and (5) the control of dust generation. The fundamental aspects of this work are applicable to respirable dust problems in both hard rock mines and coal mines, and to other dusts, such as those generated by diesel equipment. The Center's interdisciplinary activities involve the training of engineers and scientists, graduate students, and undergraduate students through their respective institutions, and technology transfer to the industry. The Center research is fully compatible

and complementary with existing Bureau of Mines activities and is integrated into the Bureau's research on dust generation, transport, and suppression. Additionally, the results of studies by the National Institute for Occupational Safety and Health (NIOSH), Division of Respirable Disease, are available through the relationship between NIOSH and West Virginia University.

SUMMARY

Health standards in the United States are among the highest in the world. Achieving these standards has often led to decreased production and increased prices to levels that make it difficult to compete with many foreign industries. The answer to many of these problems lies in the development of new and advanced respirable dust control techniques. This overview has identified some of the major technological hurdles that have been overcome and provided some insight into current and future approaches underway to remove remaining obstacles and provide the United States with the most advanced mining industry in the world from a respirable dust standpoint. The necessary developmental research is costly and time-consuming. The long-term, high-risk aspects of this effort are being addressed by the Bureau and the Generic Mineral Technology Center for Respirable Dust.

To date, approximately 35% of the coal mining industry has been placed on more stringent dust standards due to quartz. Control techniques must be improved if mandated levels are to be met. As longwall production increases, dust levels will also increase. Thus, the Federal dust standard will serve to restrict future production unless new dust control technology is developed.

In sum, significant benefits to mineworker health have resulted and are expected to continue from the scientific, engineering, and medical research being conducted jointly by the Bureau and the Generic Mineral Technology Center for Respirable Dust.

NOISE

Noise is often regarded merely as a nuisance. In reality, however, it is a widespread occupational health problem. The extent and severity of the noise problem in mining was revealed in a 1976 study by NIOSH. This study revealed that underground coal miners had measurably worse hearing than the national average population. For example, the median hearing loss of retired miners was 20 decibels (dB) greater than that of the general population. Figure 12 shows that at age 60, more than 70% of all miners had a hearing loss greater than 25 dB, and about 28% had a hearing loss greater than 40 dB. Miners experience greater hearing impairment than most other industrial workers because of their greater exposure to noise. Because this hearing loss occurs gradually over many years, the individual is not aware of it until he or she notices difficulties in communicating with other people.

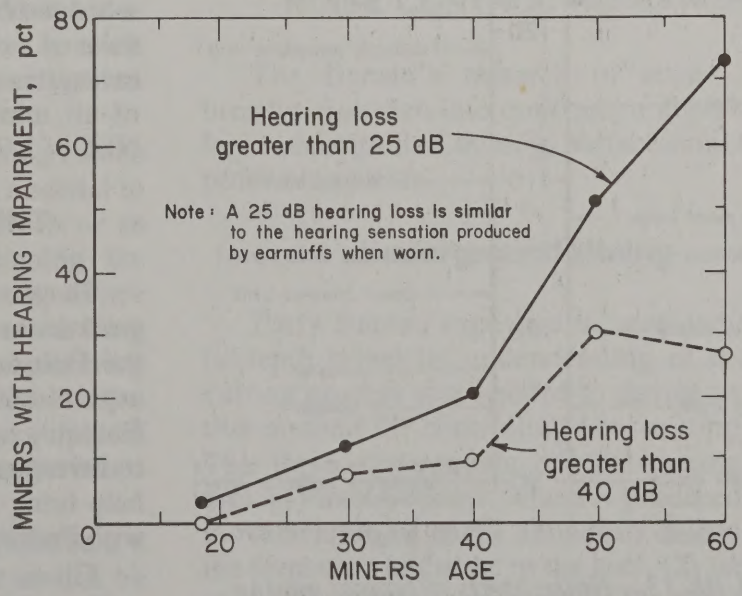


FIGURE 12. - Hearing loss of coal miners as a function of age.

FEDERAL NOISE REGULATIONS PERTAINING TO MINING

The Federal Government regulates the noise exposure of miners under the Federal Mine Safety and Health Act of 1977. This act covers surface and underground operations of metal and nonmetal mines as well as coal mines. The Code of Federal Regulations defines permissible noise exposures for all mineworkers in terms of noise dose, which includes both the level and duration of the noise. Noise level is measured in decibels using a sound level meter, with the A-weighted decibel (dBA) being the unit of measure used in the regulations. The A-weighted scale takes into account the fact that the human ear is more responsive to high-frequency sounds (1,000 to 5,000 hertz (Hz)) than low-frequency sounds (below 1,000 Hz). Figure 13 shows the typical A-weighted noise levels of common mining machinery.

The table below indicates the relationship between noise level and allowable exposure time per day for mining operations. Exposure to noise levels below 90 dBA is not regulated. It is evident from the table that the higher the noise level, the shorter the allowable exposure time is. At 90 dBA, the maximum allowable exposure time is 8 hours per day. Each 5-dBA increase in noise level reduces the maximum allowable exposure time by one-half. Exposure to continuous noise levels higher than 115 dBA is not permitted by law.

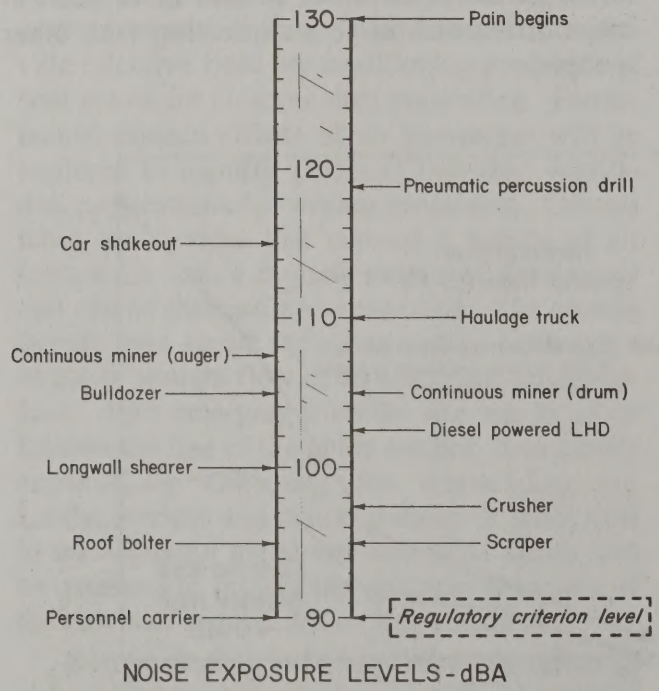


FIGURE 13. - Noise levels of typical mining equipment.

Noise level, dBA	Allowable exposure time, hours
90	8.0
92	6.0
95	4.0
97	3.0
100	2.0
102	1.5
105	1.0
107	0.75
110	0.50
115	<0.25

In practice, compliance with noise regulations is determined by measuring each worker's noise exposure index (NEI), which includes both the noise level and the exposure time at each level. NEI is defined as:

$$NEI = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots,$$

where C_1, C_2, etc., are the actual times the worker was exposed to each noise level above 90 dBA, and T_1, T_2, etc., are the allowable exposure times for the noise levels to which the worker was exposed. A worker is overexposed when the NEI value exceeds 1. Based on the results of extensive noise surveys and dosimetric measurements, it is estimated that 30% or more of all miners are exposed to a noise dose, or NEI, of 1.0.

THE BUREAU'S APPROACH

Because noise affects such large numbers of workers in all segments of the mining industry, the Bureau became involved in many different aspects of noise control. The objective of the Bureau's noise control research efforts has been to investigate techniques that would, if adopted, help bring the mining industry into compliance with Federal noise regulations.

Given that the mining noise problem is so widespread, the Bureau used the following cri-

teria in formulating its research strategy: (1) the problem must result in serious worker overexposure and risk of hearing loss, (2) it must affect a large number of mineworkers, and (3) the mining industry itself must be incapable of solving the problem because of insufficient financial resources or technical expertise. For example, the Bureau has conducted long-term basic studies into all the major noise-generating mechanisms of the coal-cutting process. This required a level of effort and technical expertise that equipment manufacturers could not provide.

FIGURE 14. - A multiboom percussion drill can subject the operator to extreme noise levels of 130 dBA.

An important aspect of the Bureau's approach to noise control is its emphasis on engineering controls for the major noise sources in the mining workplace. Although Federal noise regulations allow the use of both engineering and administrative (e.g., job switching) controls as the primary means of addressing mining noise problems, Bureau research has shown that engineering controls can often be more effective. For example, job switching during any given day would be nearly impossible in many metal and nonmetal mines because of long travel times between noisy and quiet workplaces. Additionally, serious safety hazards could result if inexperienced workers were switched into noisy jobs that require high levels of skill. Finally, if an engineering control can be applied successfully to the noise source, administrative controls will be unnecessary, and the solution will generally be more permanent.

Engineering noise controls in mining can be as simple as adding sound-absorbing material to the inside of a bulldozer operator's cab or as complex and demanding as redesigning the inner workings of percussion drills to produce less noise while maintaining the same drilling power (fig. 14). The two basic engineering noise control strategies are: (1) to install noise control treatments on existing mining equipment (the retrofit approach) and (2) to design inherently quieter mining equipment.

The retrofit approach is usually preferred if a straightforward noise control technique can be employed, and it is especially desirable in the capital-intensive mining industry. If a retrofit noise control treatment is successful, it can often allow timely and relatively inexpensive compliance with Federal noise regulations. An acoustical cab for a bulldozer operator is one example of a successful application of the retrofit approach. However, even in this simple case, careful application of the noise control treatments is essential for optimum noise reduction. Unfortunately, the retrofit approach is not appropriate for many other existing pieces of mining equipment.

NOISE CONTROL RESEARCH

The Bureau's research in noise can be broadly classified into three major areas of mining: underground mining, surface mining, and processing plants.

Underground Mining

Early Bureau experiments revealed that an in-depth scientific understanding of the coal-cutting process was needed to devise an effective method for controlling coal-cutting noise. The three components of coal-cutting noise are: (1) fracture noise, which is produced by the movement of air to fill the voids resulting from the formation of cracks in the coal; (2) face radiation, the vibratory response of the coal face itself; and (3) cutting head vibration, which

results from the transfer of cutting forces from the bits to the rotating head assembly. The three basic goals of the laboratory studies were (1) to identify the dominant component of coal-cutting noise (fracture, face radiation, or cutting head vibration); (2) to determine the magnitude of coal- and shale-cutting forces; and (3) to show how the coal- and shale-cutting noise level can change due to machine operating parameters such as depth of cut, cutting speed, bit style, etc.

One of the most important findings of the laboratory tests was that coal resists the advance of a cutting bit in a manner analogous to the action of a spring. The cutting force of the bit increases until the tensile stress in the coal initiates a localized brittle fracture. This fracture propagates out from the point of force application for a small distance. The bit continues to advance through fractured coal, meeting relatively little resistance until it again contacts unfractured coal, when the process is repeated. The results of this research were used to design noise-reduced cutting heads for longwall shearers and auger miners.

The laboratory studies described above greatly aided in the design of a reduced-noise auger cutting head. Since coal-cutting forces are predominantly low-frequency forces, the auger design was based on reduction of its vibratory response to low-frequency excitation forces. The cutoff frequency for the standard auger cutting head was found to be approximately 100 to 200 Hz while cutting synthetic coal. The standard auger-miner cutting head consists of a central cylindrical core surrounded by two helixes. The cutting helix contains all the cutting bits; the bitless, or conveying, helix helps transport cut coal to the conveyor of the miner. These helixes vibrate violently, like high-powered speakers, when excited by coal-cutting forces. Since they are the primary noise sources on the cutting head, the design effort was directed at reducing helix vibration. The structural response characteristics indicated that the reduced-noise auger design would have to (1) increase the first natural frequency of the helix and (2) increase the amount of damping at its resonant frequencies.

Several methods were used to stiffen and damp the auger helixes. However, the design found most suitable for in-mine use was the sand-filled auger. First, the conveying helix was removed. Extensive in-mine tests of the reduced-noise augers showed that the single remaining helix was sufficient for both cutting and conveying. Next, the helix was stiffened by enlarging the auger's core size and adding a "conical helix stiffener." The larger core helped reduce helix vibration by decreasing the helix's height. The conical helix stiffener was a second helix that was leaned against and welded solidly to the main helix to act as a continuous support. The addition of the stiffener resulted in the formation of three cavities with triangular cross sections. These triangular cavities were filled with sand and sealed. The sand added mass, which further reduced the vibration of the helix and helped dissipate its bell-like ringing sound at its resonant frequencies. The added mass did not hamper the auger's performance because it merely replaced the mass lost when the conveying helix was removed.

A set of reduced-noise augers was tested for approximately 6 months in an underground coal mine. Although the miners were initially skeptical about the new auger design, they were completely satisfied with its performance by the end of the test period. More importantly, the new augers resulted in substantial noise reductions—10 dBA at the jacksetter position (98 dBA overall noise) and 6 dBA at the operator position (96 dBA overall noise). This reduction was sufficient to eliminate the cutting head as a contributor to operator noise. The 10-dBA reduction at the jacksetter position resulted in a fourfold increase in allowable operating time—from 45 minutes to almost 3 hours. The conical helix stiffener and sand can be installed relatively simply by most mine shops. The reduced-noise augers are also available from the auger manufacturer.

Noise levels at the lead drum operator position of a longwall system are typically in the 100- to 105-dBA range. The close proximity of the shearer operator to the coal-cutting process is the main reason for these high noise levels. The longwall shearer is highly responsive to coal-cutting forces, i.e., the natural vibration frequencies are all below 200 Hz, making it susceptible to excitation from the low-frequency forces that characterize coal cutting. Additionally, it is made of solid steel plate, which has very poor damping properties. Consequently, it exhibits a strong vibrational response at higher resonant frequencies that would otherwise be

out of the coal-cutting excitation range. Because of the cutting head vibrational characteristics described above, a twofold approach was taken in the design of the noise-controlled head. First, the stiffness of the helixes and face ring was increased to raise their first natural vibration frequencies above the region where coal-cutting forces are strongest. Second, the damping of the core was increased as much as possible because this structure was not amenable to stiffening treatments.

The design and overall appearance of the noise-controlled longwall shearer cutting head were significantly different from those of a standard head. The core of the new shearer drum consisted of the standard core surrounded by a constrained-layer damping treatment. The most important and novel feature of the noise-controlled head was its bit mounting scheme. On standard heads, the bit blocks are mounted on top of, or embedded in, the helixes; on the noise-controlled head, each bit block was mounted on its own massive, rigid stand. The first and second natural vibration frequencies of each stand were approximately 1,000 and 3,500 Hz, well above the dominant excitation frequencies produced by coal cutting. This "bit stands" design allowed for the complete removal of the helixes and face ring, thereby eliminating the most significant noise-radiating structures on the machine.

Noise measurements at the lead-drum operator position showed that the noise-controlled head provided a 5- to 6-dBA noise reduction compared with a standard head on the same shearer under the same cutting conditions. Overall noise levels were approximately 95 dBA with the noise-controlled head and 100 to 101 dBA with the standard head. This increased the allowable exposure time per shift from 2 to 4 hours. The operational performance of the noise-controlled head was excellent despite the miners' initial skepticism toward the "radical" head design. The cooperating mining company was well pleased with the overall performance of the noise-controlled cutting head. During its 7-month period of underground operation, it extracted more than 425,000 tons of coal without failure.

In addition to being exposed to noise generated during the cutting process, most miners are also affected by noise produced by the armored discharge conveyor that is an integral part of the continuous miner. The basic noise generating mechanisms associated with the conveyor are: (1) scraping and slapping of the chain and flights against the upper and lower decks and (2) impacts at numerous discontinuities along the conveyor deck. Most of the Bureau research on conveyor noise was conducted in an aboveground test facility. Prior to the installation of any treatment, the overall noise level at the operator's position was 101.5 dBA. Constrained-layer damping was relied on as the principal method of control, with the results of treating individual sources shown below:

Treatment	Result, dBA[1]
None (untreated conveyor)	101.5
Lower deck damped	101.0
Upper deck damped	97.0
Installation of upper deck wear strips.	96.5
Sidewalls damped	95.5
Large-diameter idler roller (substitution).	93.0
Isolation of take-up plate	91.5
Upper deck wear strips cut	93.0
Installation of lower deck wear strips.	91.0
Lower deck hole blocked	89.5

[1]Cumulative.

A significant reduction of 12 dBA was achieved in this aboveground test. The constrained-layer damping technique as applied to the conveyor decks was subsequently adopted by a continuous miner manufacturer and is now offered to the industry as a new machine option.

The most effective retrofit treatment for a standard stoper drill included a jacket-type muffler surrounding the drill body and air exhaust port. Drill steel noise was partially abated by the addition of a 6-inch-long collar near the bottom end of the steel. Retrofitted stopers (jacket muffler only) were tested in 15 operating underground coal mines, and muffled-versus-unmuffled noise reductions of 7 to 8 dBA were consistently obtained. The typical muffled noise levels (105 to 106 dBA) were low enough to permit a doubling of the allowable operating time per shift. Retrofit kits similar to those tested are now commercially available for several models of stopers.

Although the stoper retrofit noise control treatments were fairly successful, Bureau studies showed that greater noise reductions and improved drilling performance would be obtained by redesigning the drill to incorporate noise-reducing features. The redesign effort included three major steps: (1) redesign of the drill-steel rotation mechanism and other drill parts, (2) development of a more effective muffler-enclosure device, and (3) development of a "shroud tube" to attenuate drill-steel noise. Six of these "quiet" drills were manufactured and tested in operating mines. All six produced noise levels of 98 to 105 dBA at the operator's position, reflecting a 10 to 17 dBA reduction versus the noise of standard stopers. Importantly, the weight and penetration rates of the redesigned drills were approximately equal to those of standard stopers. These drills are now commercially available.

The diesel-powered load-haul-dump (LHD) vehicle was identified as a high-priority candidate for noise control because LHD operators are often overexposed, there is a large population of LHD machines, and the LHD is considered one of the most difficult machines to treat with regard to noise control. As with other equipment, the Bureau investigated both retrofit and redesign approaches to the LHD noise problem. The major noise sources were identified to be the transmission, engine, and cooling fan. Transmission noise was dominant because the transmission compartment was immediately adjacent to the operator's compartment. Airborne transmission noise was treated by sealing several holes between the two compartments and installing composite foam-and-plate linings on the top and forward sides of the transmission compartment. Structure-borne transmission noise was treated by mounting the transmission on specially designed rubber vibration-isolation pads and installing similar materials around the underside of the top cover. Engine airborne noise, the second major noise source on the LHD, was treated primarily by building an acoustical enclosure around the engine. The sides of the enclosure were lined with noise-absorbing polyurethane foam. Structure-borne engine noise was treated by welding triangular stiffening gussets to the frame rails on which the engine was mounted. The cooling fan was located at the rear of the engine compartment. A fold-down baffle that covered the cooling fan outlet received the same foam-and-plate treatment as the transmission cover, and the walls surrounding the fan outlet were treated with polyurethane foam.

The noise-controlled LHD was then tested in an underground gypsum mine. Operator noise levels for the two loudest stationary LHD modes (high idle and torque converter stall) ranged from 92.5 to 93 dBA, which was approximately 7 to 9 dBA quieter than in the untreated vehicle.

Although retrofit LHD noise control treatments were successful, incorporation of these treatments in a newly designed vehicle represents a more cost-effective approach. Under Bureau contract, a major LHD manufacturer incorporated noise control treatments into two of its new machines—one with an 8-cubic-yard (yd^3) bucket capacity, the other with a 2-yd^3 bucket capacity. The redesign approach was somewhat similar to the retrofit approach. Preliminary diagnostic tests were performed on the manufacturer's standard design LHD vehicles before treatments were designed. Since the manufacturer was not constrained by existing machine dimensions, better fitting acoustical treatments and mechanical components were designed and installed.

Diagnostic tests revealed that the three major noise sources on the standard design LHD's were again the transmission, engine (including intake and exhaust), and engine cooling fan. Therefore, the manufacturer installed noise control treatments similar to the retrofit treatments described earlier. Additionally, the manufacturer placed exhaust mufflers on both sides of the engine, lined the interior surfaces of the operator's compartment with acoustical foam, and mounted the transmission on rubber vibration-isolation mounts. These treatments were much easier to incorporate in the redesigned machines than in the retrofitted machine. Aboveground tests of the redesigned LHD's revealed a 9.3-dBA noise reduction for the 8-yd^3 LHD (from 99.0 to 89.7 dBA) and a 10.3-dBA reduction for the 2-yd^3 LHD (from 101.1 to 90.8 dBA).

Surface Mining

A comprehensive noise survey of surface mining operations identified the following machine types and their contribution to the noise overexposure problem:

Equipment type	Percent of total overexposed operators
Bulldozers	48.0
Front-end loaders	15.5
Haulage trucks	8.5
Draglines	8.0
Scrapers	5.5
Overburden drills	2.0
Highway trucks	0.5
All others	12.0

Several types and models of surface mining equipment now have factory-installed acoustical cabs, but many older bulldozers and front-end loaders do not. Therefore, the Bureau developed acoustical cab retrofit treatments for two popular models of each of these two machines. Although the design details of each machine are somewhat different, the same four basic treatments were used: (1) installing a muffler on the diesel engine exhaust, (2) sealing numerous holes in the floor and dashboard of the operator's station, (3) adding sound-absorbing materials under the ROPS-FOPS and under the cover of the hydraulic tank, and (4) installing vibration-isolation materials between the engine and dashboard. Additionally, windshields were installed on the two dozers that originally contained only ROPS-FOPS. The windshields were extremely important because they blocked the direct path between the diesel engine (the largest single noise source on the machines) and the dozer operators. Seals were also installed around the doors of the cab-equipped D-9 dozer. The noise reduction levels achieved through these retrofit treatments is shown below.

Model	Before treatment, dBA	After treatment, dBA	Noise reduction, dBA
Caterpillar D-9G:			
ROPS-FOPS only.	105	94	11
Cab (nonacoustical).	100	90	10
International Harvester TD-25C; ROPS-FOPS only.	102	91	11

Although about 40% of the front-end loaders surveyed were equipped with factory-designed acoustical cabs, the remaining 60% required some type of retrofit to upgrade the existing cabs' acoustical performance. The treatments were similar to those installed on the cab-equipped bulldozer. Noise reductions of 11 to 12 dBA were achieved on the two machines that were retrofitted.

As a result of this highly successful effort to control noise from bulldozers and front-end loaders, noise control handbooks were prepared for each of these machines. The handbooks served as the basis of a series of nationwide workshops sponsored by the Bureau in all major mining communities. Several thousand copies of these handbooks have already been distributed.

Processing Plants

The Bureau's most successful project in coal preparation plant noise control was conducted at Consolidation Coal Co.'s Georgetown Preparation Plant, Cadiz, OH. This was a cooperative effort in which Consol provided both the necessary noise control materials and on-site labor for installation. The work consisted of three major elements: (1) identification of the most serious noise sources, (2) selection and installation of retrofit noise control treatments, and (3) both short- and long-term evaluations of the durability and acoustical effectiveness of the retrofit treatments. The major sources with before and after noise levels are shown below:

Equipment	Before treatment, dBA	After treatment, dBA
Classifying screens	102-104	96-97
Centrifugal dryers	95-103	89-92
Vibrating screens	101	96
Rock crusher	93-100	91-92
Clean coal desanding screens	96- 97	93
Secondary sizing screens	95- 97	93
Baum jigs	94- 97	91-93
Middling shaker screens	94- 97	92
Coal crushers	96	90
Flight conveyor	94- 95	92-93
Picking table	94	90-92
Primary screens	94	91

Most of these noise sources received one or more of the following noise control treatments: (1) resilient screen decks, (2) resilient impact

pads, (3) chute liners, and (4) loaded-vinyl curtains. The resilient screen decks consisted of elastomeric top surfaces (rubber or urethane) bonded to metal bottom layers. The impact pads and chute liners were also made of elastomeric materials. These three treatments reduced the noise generated by material (coal or rock) falling or sliding on bare steel. The loaded-vinyl curtains were used to enclose several particularly noisy pieces of equipment. In most cases, these curtains consisted of a series of vertical strips of the loaded-vinyl material held together along the edges with Velcro fasteners. This construction allowed workers to inspect the enclosed equipment without removing the entire curtain.

SUMMARY

Hearing loss due to noise in the mining environment is a serious occupational health hazard. The Bureau has addressed this problem by conducting a wide variety of noise control research projects in all areas of mining. Because the mining environment cannot be easily treated to reduce noise levels, research has focused on noise control treatments for the machines used in mining. Retrofit techniques for existing equipment have been pursued whenever possible while, in other cases, equipment component redesign has been found to be more effective.

The Bureau's current research activities continue to be responsive to the noise problems faced by mineworkers. A study of the effectiveness of personal hearing protectors (earmuffs) under field conditions is nearing completion. A better understanding has been developed of the effects of typical in-mine physical agents on the performance of acoustical materials. Modeling of the spatial distribution of sound levels in typical mining environments is underway. The Bureau's Mining Noise Laboratory provides Bureau personnel with a well-controlled acoustical environment in which detailed studies of the noise-generating mechanisms of mining equipment can be conducted. This approach is expected to be more cost-effective than field demonstrations and should yield results that can be implemented in the future by equipment manufacturers and users to create a quieter mining environment.

RADIATION

Following the passage of 30 CFR 57.5038, the Bureau of Mines initiated a research program aimed at measuring and controlling the exposure of miners to radon decay products. As used here, the term "radon decay products" (working levels) refers to alpha-emitting radionuclide particles that enter the miner's lungs with the possibility of causing lung cancer. Over the past 20 years, Bureau research has addressed three principal areas:

- Monitoring of airborne radioactivity using the following technologies: continuous radon decay product (working level) monitor, continuous radon monitor, continuous environmental radon monitor, and the personal radon decay products dosimeter (figs. 15-16);
- Sealants applied to mine walls, backs, and floors to stop radon from emanating into the mine atmospheres;
- Air cleaners to remove radon decay products from mine air.

MONITORING

Continuous Working Level Monitor

Developed in the mid-1970's, the continuous working level monitor proved to be reliable in harsh mine environments. During many years of usage by Bureau personnel, by teams from universities, and eventually as manufactured by a private contractor, no significant problems have been encountered with this monitor. It also proved to be successful in measuring outdoor radon decay products activity for 2 years at a U.S. Environmental Protection Agency Superfund site near Denver, CO.

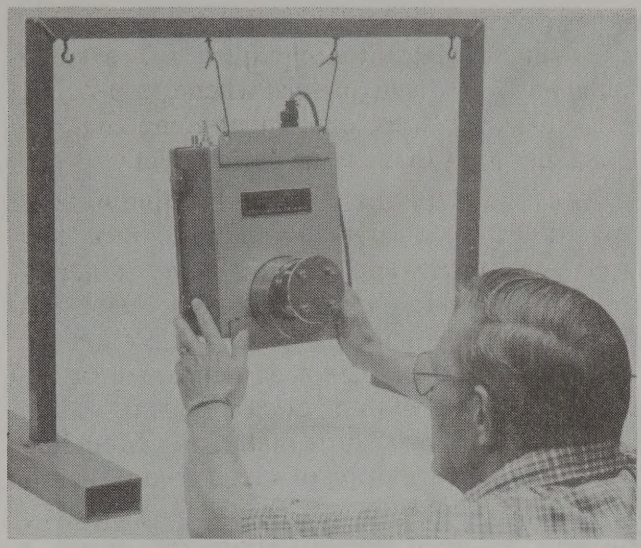


FIGURE 15. - Working level detector portion of the continuous working level monitor.

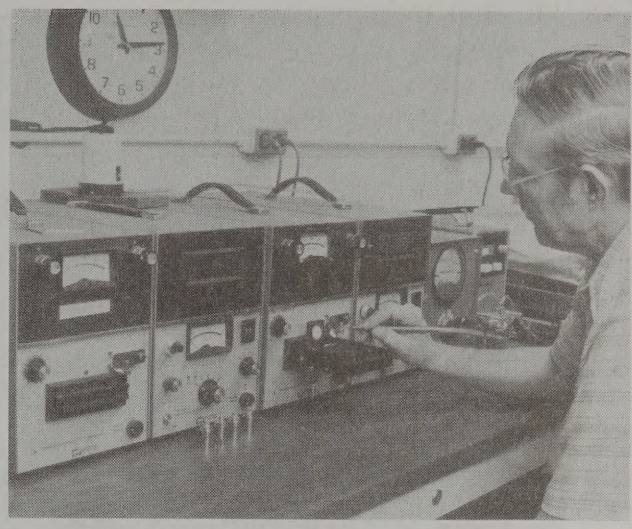


FIGURE 16. - Thermoluminescent readout of alpha detectors used in Bureau-developed personal working level dosimeters.

Environmental Radon Monitor

As a spinoff of the continuous working level monitor, the high-sensitivity environmental radon monitor was developed in the late 1980's. This monitor successfully performed at the above-mentioned Superfund site for 2 years. The sensitivity of this monitor is about 50 times greater than that of commercially available radon detectors.

Continuous Radon Monitor

For higher radon concentrations in uranium mines, a continuous radon monitor was developed in the mid-1970's. Many of these monitors performed successfully in harsh mining conditions for more than a decade.

Personal Radon Daughter Dosimeter

Because the area monitors described above did not really measure airborne radioactivity in close proximity to miners, personal monitors belt-worn by each miner were developed in the late 1970's and early 1980's. These dosimeters were tested in very harsh mining conditions while worn by miners and were found to be reliable. During the same tests, grab sample monitoring was also performed. There was a poor correlation between the two sets of data, indicating that grab sampling does not accurately reflect the exposure of miners to radon decay products. Bureau personnel used these dosimeters during experiments in uranium mines, with good results.

SEALANTS

Application of various mine surface sealants proved to be only about 60% efficient in preventing radon gas from entering the mine atmosphere. In addition to excessive cost, they were difficult to apply. As a result of this research, ventilation clearly remains the most efficient and cost-effective means of controlling the exposure of miners to radon daughter decay products.

AIR CLEANERS

The research and development of efficient, low-maintenance, and mineworthy air cleaners occurred from 1978 to 1985 (fig. 17). The resulting prototype was successfully tested for 6 months in an operating uranium mine. The specially developed and rather expensive filters worked without needing to be changed for the entire duration of the tests. The removal rate for radon decay products was 95% to 98%, while the removal rate for small aerosols (0.05 to 0.5 micrometers) was only about 50%.

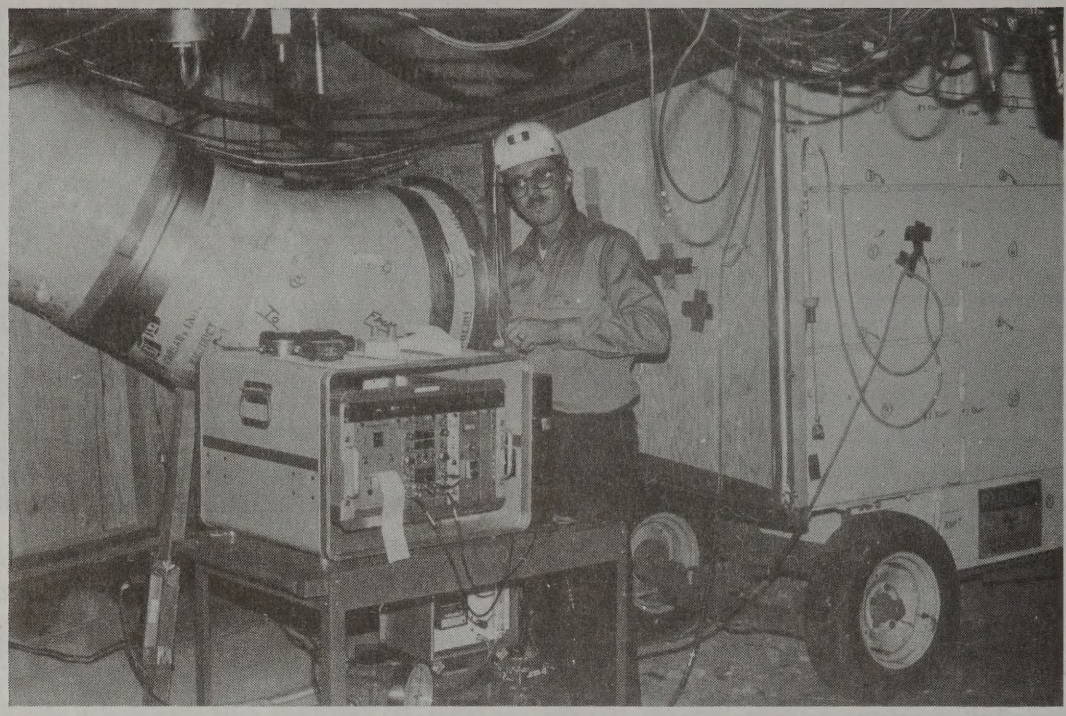


FIGURE 17. - Testing of radon decay products air cleaner in the Twilight Mine.

INDUSTRIAL HYGIENE

Toxic gases are produced during mining and minerals processing by diesels, explosives, and solvents and processing chemicals. An effective means for improving and maintaining workplace air quality was required. The Bureau's goal was to provide monitoring methods and a specific measurement technology to control worker exposure to these gases. In the area of diesels, additional improvements on emission control technology were an obvious necessity.

TOXIC GASES

The Bureau's research on toxic and flammable gas sensors included investigations of solid-state semiconductor sensors for CO and CH_4; electrochemical sensors for CO, NO, NO_2; color-indicating gels for an early warning CO badge; passive chemical adsorption for NO_2; and novel infrared techniques for CH_4, CO, and CO_2. Applications of these techniques were for personal alarms, portable survey and monitoring instruments, on-board diesel vehicle alarms for warning of exhaust buildup, and permanently installed mine monitoring systems. Because some toxic gases such as CO are products of fires, the developed technology also found application in fire detection systems. Bureau research in the early 1970's included the development of an air quality monitoring strategy manual for the complex situation of diesels in underground mines.

The Bureau achieved technical success in a number of its efforts in the 1970's and early 1980's. A passive sampler for NO_2 (fig. 18) and a similar device for NO_x were developed in conjunction with New York University Medical Center. This device was used extensively by the Government (NIOSH, MSHA) to survey mines using diesels. Bureau-sponsored research with General Electric Co. yielded innovative solid polymer electrolyte electrochemical cells for detecting CO and, with limited success, NO and NO_2. Personal and portable instruments based on this technology were available commercially. Under Bureau-sponsored research with The Bendix Corp. and Mine Safety Appliances Co., improved machine-mounted methane detector systems were developed and evaluated. These innovations were the forerunners of today's improved sensors.

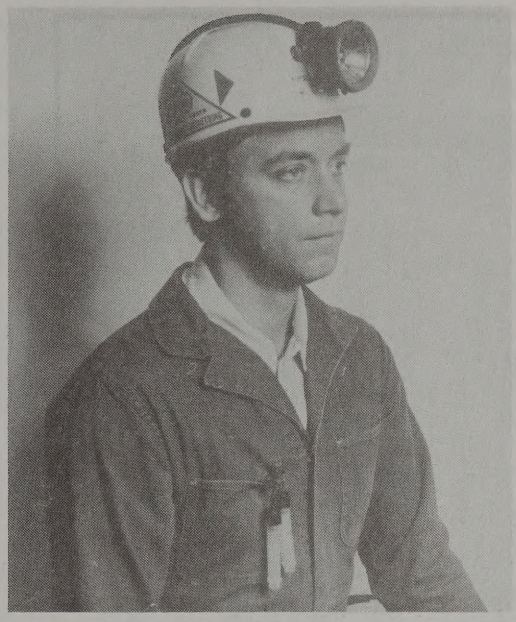


FIGURE 18. - Passive sampler for NO_2 worn on coveralls.

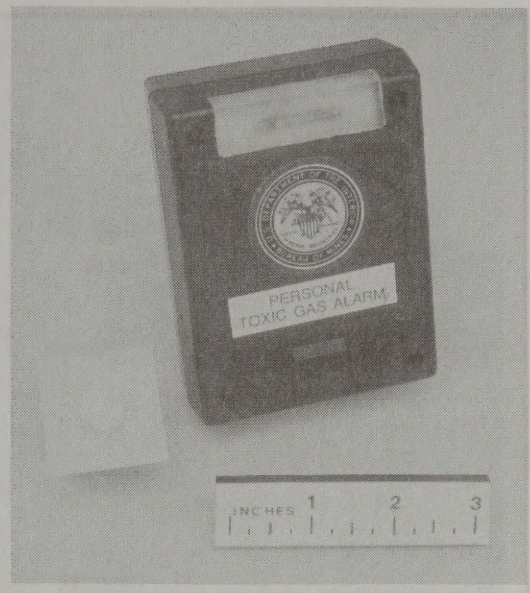


FIGURE 19. - Personal toxic gas alarm (PERTGAL).

Another Bureau-sponsored contract with Andros Analyzers, Inc., Berkeley, CA, resulted in a robust CO_2 monitor for mounting on-board diesel vehicles to monitor the effectiveness of ambient ventilation to remove diesel exhaust. Bureau research indicated that excessive CO_2 is an excellent indicator of a potential toxic buildup of CO and is a reasonable index of other diesel pollutants. Several production prototype units were used extensively in Government field research, but the product has not commercialized to date owing to the small size of the mining market and lack of a parallel market in other industrial environments.

In 1988, Bureau researchers developed a personal toxic gas alarm (PERTGAL) that warns the wearer to don protective breathing equipment and escape from an area where toxic gases are at hazardous levels, especially carbon monoxide and hydrogen sulfide (fig. 19). The device is small, belt-wearable, powered by an ordinary 9-volt alkaline transistor battery, and alarms with a flashing strobe lamp. Gases react with a small chemical disk containing silica gel impregnated with a palladium salt, changing the disk from brown to gray. The circuitry in the device is intrinsically safe, and the toxic gas-sensitive disk is commercially available, inexpensive, and replaceable.

DIESEL RESEARCH

To reduce worker exposure to diesel exhaust emissions, the Bureau has successfully developed and tested several new control technologies. These developments will enable the mining industry to comply with increasingly stringent health and safety standards.

Diesel particulate matter is the greatest concern because it is almost entirely respirable in size, with 95% of the particles having a mass median diameter less than 1.0 micrometer. A permissible exposure limit for diesel particulate matter is currently being considered by MSHA.

The Bureau has determined the relationships between engine condition, maintenance practices, emissions, and time in service. Proper engine maintenance was found to result in lower fuel consumption and lower levels of exhaust pollutants. Changes induced into a diesel engine that resulted in higher than recommended fuel-air ratios or accelerated engine wear caused degradation of engine emissions (fig. 20), efficiency, and durability. Diesel engines in underground service can be expected to perform several thousand hours with minimal degradation of exhaust gas characteristics and performance when properly maintained.

The Bureau entered into an agreement with the Canada Centre for Mineral and Energy

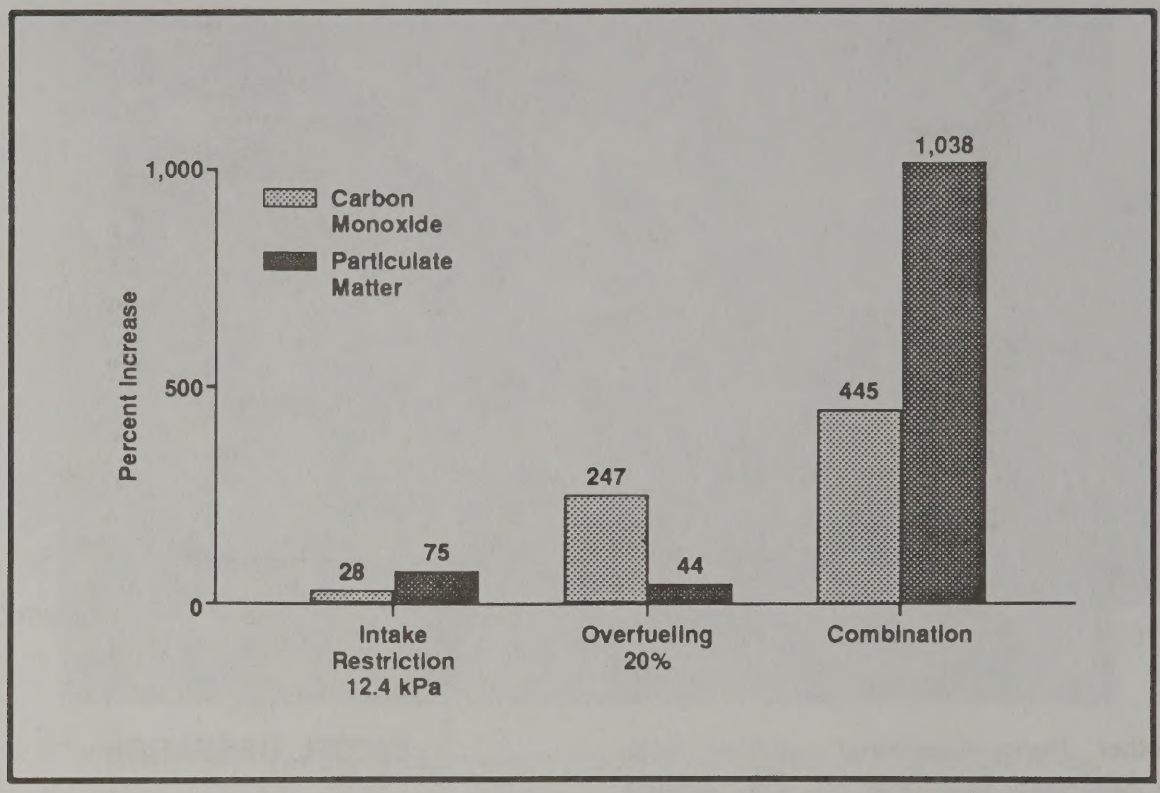


FIGURE 20. - Effects of engine intake air restriction and overfueling on carbon monoxide and particulate matter emissions.

Technology (CANMET) and the Ontario Ministry of Labour to cooperate on developing diesel exhaust control technology. To control diesel particulate matter, it was determined that the ceramic (wall-flow) diesel particulate filter (DPF) was very promising (fig. 21). The DPF is being increasingly used on equipment in nongassy metal and nonmetal mines. The ceramic filter significantly lowers the concentration of diesel particulate matter in the exhaust, reducing worker exposures. Research by the Bureau and others has shown that the DPF has a particle collection efficiency of 85% to 95%. Work is ongoing to expand the use of the ceramic particulate filter to coal mine equipment.

The Bureau, in cooperation with Donaldson Co., Inc., and Utah Fuel Co., successfully developed a disposable diesel exhaust particulate filter (fig. 22). Tests in an underground coal mine showed diesel soot reductions of 95%. The disposable filter is similar to intake air filters used on large diesel engines. The filter material can be made of various types of treated natural or synthetic materials. The filters tested had a useful service life of about 1.5 shifts and cost about $40.

The Bureau has found two diesel fuel additives that reduce diesel soot emissions. An iron-based additive—ferrocene—reduced soot 37%. A barium-based fuel additive was most effective at high engine loads. The soot reductions ranged from 10% at light engine loads to 75% at full loads.

The successful development of a pollution-free, hydrogen-powered prototype vehicle is a major advancement in mine equipment. The Bureau and EIMCO Mining Machinery International codeveloped a safe, nonpolluting power source for underground mining equipment using hydrogen as fuel. The conceptual design of the system is shown in figure 23. The fuel storage system incorporates separate modules (similar to heat exchangers) containing hydrogen in hydride form. The hydrogen diffuses into the crystal structure of metal powders where it exists as an interstitial chemical compound. The fuel modules utilize waste heat from the engine's cooling system to break the chemical bonds,

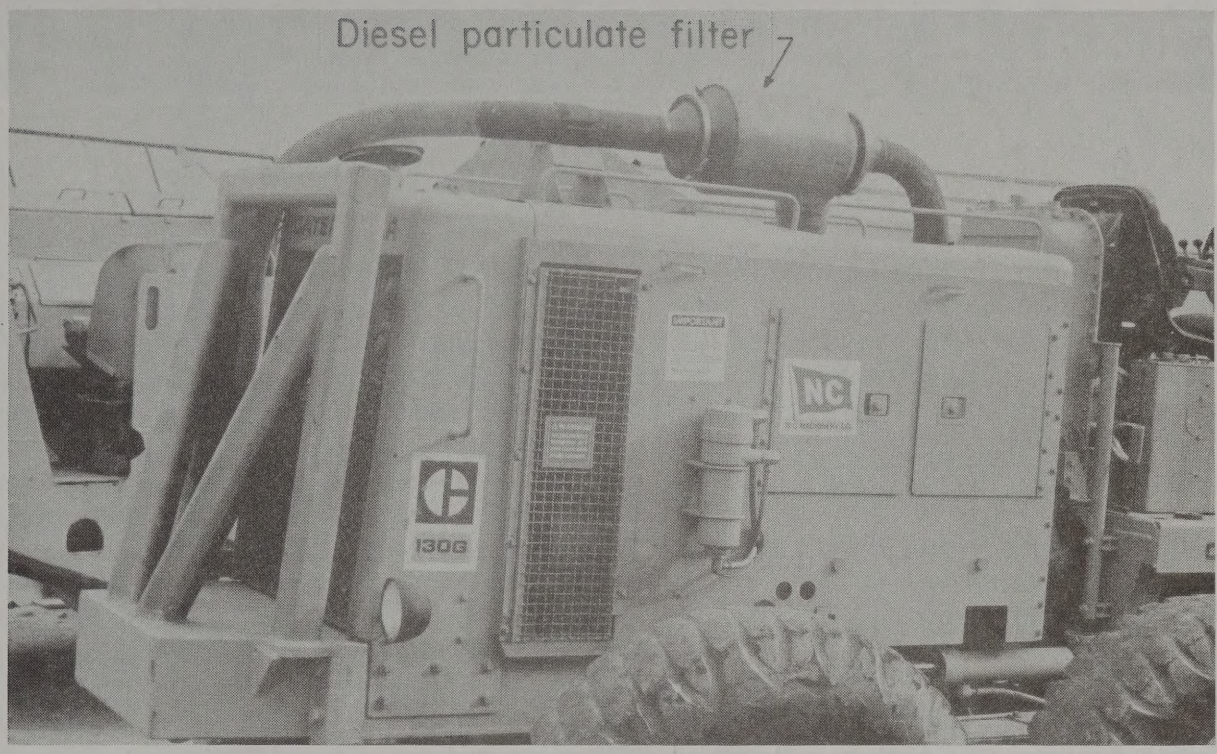


FIGURE 21. - A ceramic (wall-flow) diesel particulate filter installation on a front-end loader used in a metal mine.

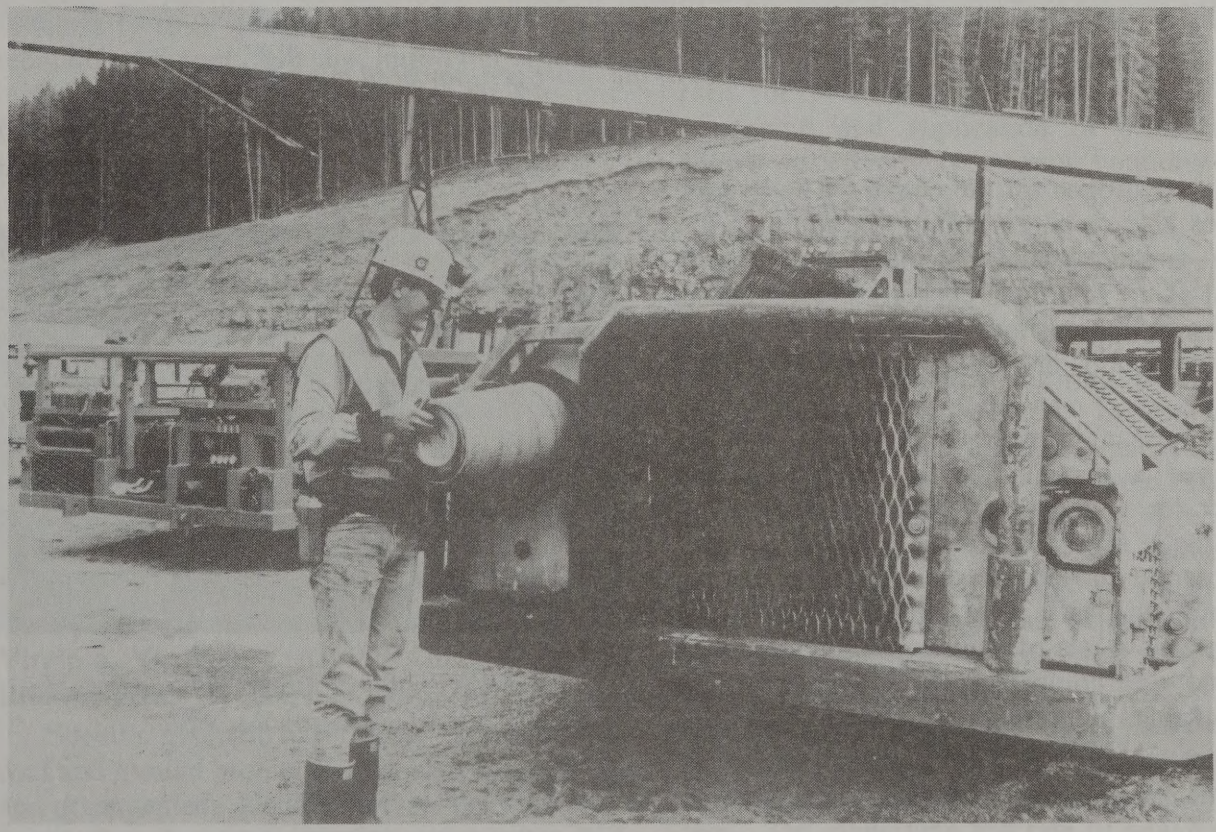


FIGURE 22. - A disposable diesel exhaust particulate filter element being replaced on a coal haulage vehicle.

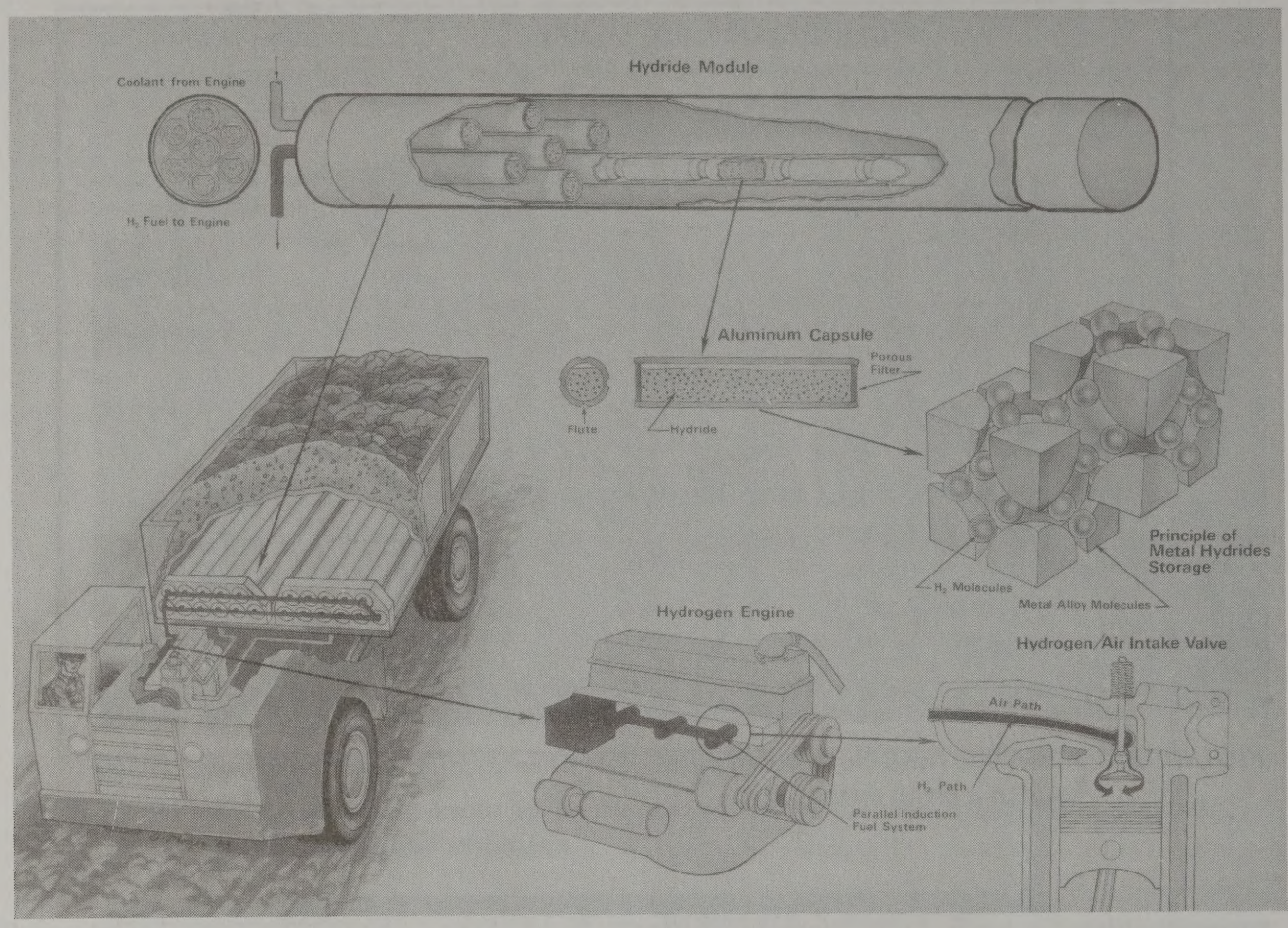


FIGURE 23. - Conceptual design of the hydrogen-powered mine vehicle.

releasing hydrogen for the engine. The hydride modules also recharge rapidly by applying hydrogen pressure while cooling them. Ninety percent of the hydrogen capacity is absorbed in 90 seconds with an ample flow of 20° C cooling water and 2.8 megapascals of hydrogen pressure.

The Bureau, in cooperation with MSHA, has developed a personal diesel exhaust aerosol sampler for underground coal mines (fig. 24). The sampler makes a size cut at 0.8-micrometer aerodynamic diameter to separate diesel aerosol from mineral dust. The sampler operates at a sampling flow rate of 2 liters per minute and is designed to be compatible with commercial personal sampler pumps.

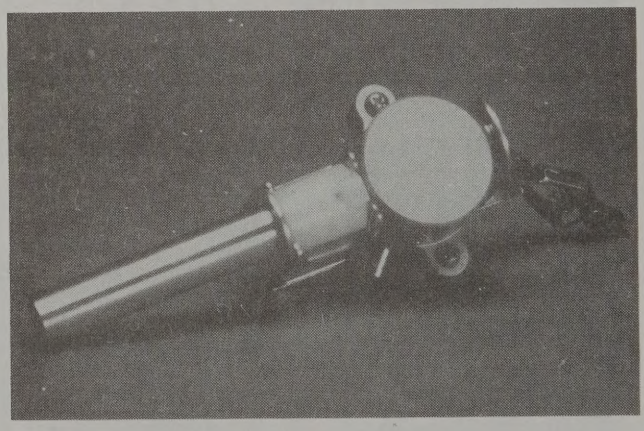


FIGURE 24. - Personal diesel exhaust aerosol sampler.

GROUND CONTROL

Because of the high incidence of roof fall injuries and fatalities, the Bureau of Mines has been investigating coal mine roof instability since the agency's inception in 1910. With the passage of the Federal Coal Mine Health and Safety Act of 1969, the Bureau intensified its ground control research, designed specifically to improve the safety of U.S. mineworkers. The primary objective has been to develop technology for reducing accidents, injuries, and fatalities due to falls of ground. Prior to and during this period, falls of roof, rib, and face posed the most serious threat to the safety of underground workers. Accident analyses for the past 50 years indicate nearly 50% of all underground bituminous coal mine fatalities were associated with roof-rib fall accidents.

In the past 20 years, Bureau ground control research has traversed a wide range of subjects. In the early 1970's, research concentrated on the reduction of roof falls by improving support techniques (roof bolting), analyzing the geologic factors contributing to ground failures, and the initial development of roof monitoring methods.

Clearly, reducing unplanned falls of roof and rib has been, and will continue to be, a necessary aspect of Bureau ground control research. This research area has involved geologic hazard detection, roof fall warning, roof deterioration studies, improved roof bolting techniques, and evaluation of bolt/anchor effectiveness. Significant research results in this area include determination of the geologic factors causing roof instability and ground problems. Hazardous roof structures and general geologic factors influencing coal mine roof instability were identified in coal mines in West Virginia, Virginia, Kentucky, Ohio, Alabama, Illinois, Pennsylvania, Colorado, and Utah.

Specific geologic hazards and their effect on roof and ground problems were also investigated and documented. Kettlebottoms—the preserved casts of ancient tree stumps, which often fall without warning—were investigated. Their occurrence and relation to mine roof stability and support were determined. Effective kettlebottom and clay vein support recommendations were developed and have become the industry standard (fig. 25). Ancient stream channel deposits (paleochannels) were investigated in a mine in southwestern Pennsylvania. It was shown that mine entries located beneath the paleochannel deposits exhibited less stable roof conditions than entries located outside the influence of the paleochannels. Furthermore, it was determined that paleochannels can be predicted by recognizing geologic features, thus allowing for modification of roof support systems, such as increased bolting patterns and other artificial supports.

Research on the effects of temperature and humidity on mine roof has shown that seasonal changes cause roof deterioration because of the detrimental action of moisture on shaley roof rock. Preventive measures such as air tempering and application of sealants were shown to effectively control humidity-related roof deterioration.

HAZARDOUS DETECTION SYSTEMS

Investigations to determine roof movement and provide early warning of impending roof failure were conducted. Instrumentation was developed that accurately measures roof movement. These include borehole extensometers, continuous roof displacement recorders, and mechanical and ultrasonic convergence meters (fig. 26). Knowledge of roof-to-floor convergence and roof strata separation can be used as an indicator of imminent roof failure. Monitoring techniques utilizing microseismics and resistivity were shown to have a high probability for successful application in a commercially practical roof fall warning system. The magnitude and rate of advance of an in-mine squeeze were determined by measuring

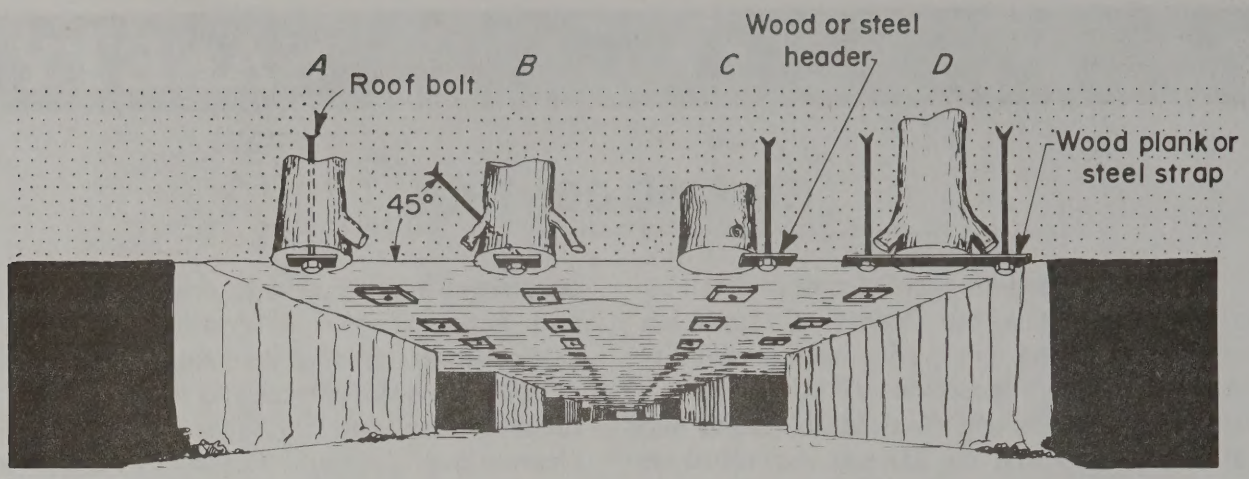


FIGURE 25. - Common methods of kettlebottom support. ***C*** *and* ***D*** *are the most effective and recommended.*

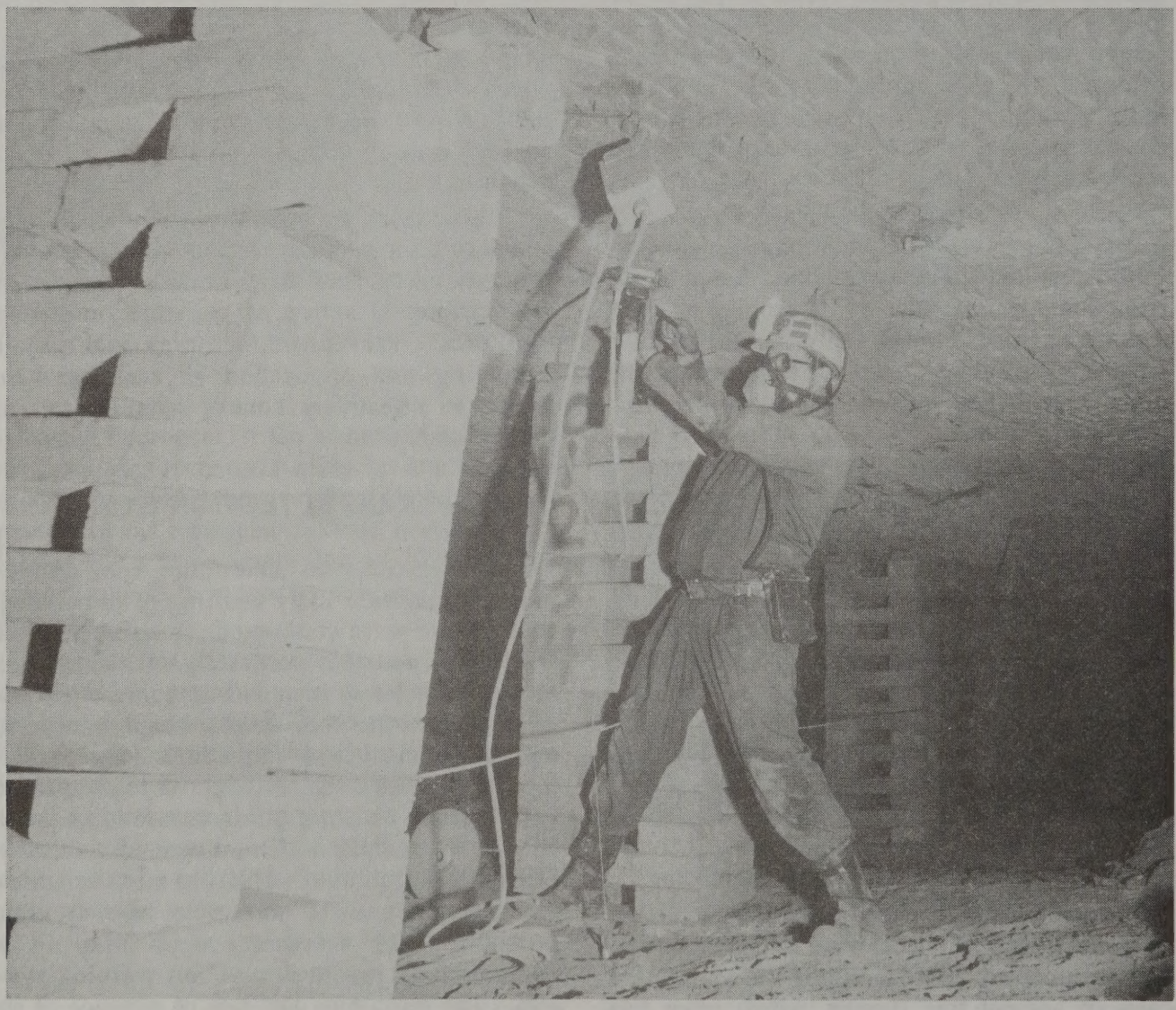


FIGURE 26. - Remote reading roof-to-floor convergence sensor assembly.

roof-to-floor convergence with a dial-gauge tube extensometer. The data, needed to determine if remedial support action was necessary, revealed that the squeeze was decelerating; thus, no corrective action, such as increased support installation, was needed.

Roof Closure Rate Devices for Retreat Mining

The Bureau has developed two intrinsically safe closure rate devices that provide the mine operator a means for predicting an imminent roof fall during retreat mining. One is a mechanical extensometer type, the other ultrasonic. The key to retreat mining is to mine as much of a coal pillar as possible, then remove both personnel and equipment before the final portion of the roof collapses. Obviously, if one knows exactly when the roof is going to collapse, personnel safety increases since (1) mineworkers receive both audio and visual warning of imminent roof failure and (2) workers are not exposed to hazards when digging out buried equipment. These devices are now being used in seven mines, six in the United States and one in Canada, and are commercially manufactured.

Geophysical Techniques

Developing and evaluating geophysical techniques for detecting ground hazards prior to mining have led to several viable hazard prediction tools. One such method, the acoustic crosshole technique, examines the coalbed and rock mass between boreholes and detects geologic hazards in advance of mining. This crosshole technology has shown great promise as a tool for real-time delineation of geologic anomalies and hazardous ground conditions. Additionally, the Bureau developed improved waveform processing and tomographic imaging capabilities to assist in the interpretation of subsurface geologic and stability conditions. These crosshole systems, together with advanced tomographic imaging utilizing curved ray paths, permit visually opaque earth structures to be viewed by acoustic waves in a manner similar to the way CAT scans view parts of the human body. Applications of the crosshole technology include detecting fractures and flaws, detecting seam offsets on faults, delineating geologic structure, and locating voids and abandoned mines.

Other effective systems, including in-seam seismic and ground-penetrating radar, detect geologic hazards in-seam and are especially useful in longwall mining. Research in remote sensing has demonstrated that geologic lineaments can be used to identify mine areas subject to potential ground instability. The lineaments are linear features on the Earth's surface and are mapped from Landsat satellite images. They are often caused by subsurface fractures that can extend through to the mine level, often disturbing the mine roof. The bulk of this research was especially useful to the mining industry for mine planning and design.

Passive Measurement Techniques

Several passive measurement techniques for monitoring safety conditions were investigated. The most important technique developed was microseismic/acoustic emission, which detects the noise produced as rocks fracture. Monitoring of the microseismic events can be used to warn of impending roof and rib failure.

In the late 1930's, two Bureau researchers, Leonard Obert and Wilbur I. Duvall, discovered low-level noises emanating from stressed rock pillars. Investigations revealed that these sounds are associated with rock failure and deformation. Over the past half-century, these types of noises have become widely known as either microseismic activity or acoustic emission. The term "microseismic" (literally, "small earthquake") often is used in the geotechnical field, while "acoustic emission" is more common in material science. The association of these emissions with material failure has prompted the development of applications in a variety of industries. The Bureau has been instrumental in developing microseismic monitoring techniques for geotechnical applications (fig. 27).

The Bureau has conducted microseismics research in the laboratory and in the field for applications ranging from in situ stress determination to pit slope stability assessment. Historically, however, the Bureau's microseismic research program has focused on applications dealing with rockbursts and coal bumps, and roof and rib instabilities. The ability to sense microseismic events at great distances

FIGURE 27. - A Bureau researcher installs sensors for microseismic monitoring in a longwall coal mine.

from their source and to determine the location of the source are key attributes of microseismics monitoring. However, a considerable research effort has been required to facilitate using these attributes. The Bureau has developed hardware needed to detect, condition, and record microseismic events, and software needed for data interpretation (e.g., source location and signal processing algorithms). From this fundamental research, specific instruments were developed, such as the Rock Burst Monitor for use in burst-prone hard rock and coal mines.

The last decade has seen a tremendous surge in computer automation in virtually all industries. The Bureau has kept pace by incorporating new technologies into the microseismic research program. Recent innovations include the development of a computer workstation-based Automated Microseismic Monitoring System, which has been deployed in bump-prone coal mines. Similar hardware improvements have been made to higher-frequency systems utilized in burst-prone hard rock mines. These improved monitoring systems allow data to be evaluated in real time so that the information will be available for mine operators to incorporate in the decisionmaking process.

ROOF BOLTS

Research to improve the roof bolting process was accomplished in three areas: bolt hardware, bolt testing, and bolt usage and installation patterns. The effect of washers and plates on bolt tension was investigated, and improved methods for more accurately controlling the tension were adopted by industry. Research to characterize bolt integrity involved the development of instruments to determine bolt tension and anchorage, and theoretical and laboratory studies of bolt integrity parameters. Research has also focused on the interaction mechanics between rock mass and support systems, and the effectiveness of inclined bolts. The instrumentation, along with the laboratory and theoretical studies, have led to a more complete understanding of roof bolt performance. Through this increased understanding, mine operators can more effectively determine the correct bolting system for specific geologic conditions.

Comparative evaluations of various roof bolt types and lengths were conducted that provided the mining industry with information to improve roof bolting and mine roof stability. Mechanical anchor, fully grouted resin, and split set bolts were some of the supports tested. The laboratory and underground testing of current and innovative roof bolt elements has provided the accepted industry standards for anchorage and load capacity of various bolting systems; the relationship of hole size, bolt diameter, and resin quantity for maximum anchorage; and the strata conditions for which each bolt type is most suited.

The Bureau researched several new roof control concepts, including a pumpable rock bolt, a yielding rockbolt, roof truss evaluations, a flexible helical rock bolt, and various cement-based bolt grouts. These studies have provided the mining industry with proven results of support effectiveness and alternatives to standard roof bolting practices under varying geologic, mining, and loading conditions.

Pumpable Roof Bolt

Remotely installing roof bolts has long been recognized as having significant safety advantages. If the roof bolt were made of a noncorrosive material and its length could be adjusted from a remote location with little effort, further safety advantages would be gained. The Bureau has developed a remotely placed pumpable roof bolt with a fiberglass core and an epoxy-type grout system. This roof bolt provides full-column support and is simply cut with a knife-type blade. This concept has received much attention both from roof bolt operators and from those required to install long cable-type bolts in metal mines. Current Bureau studies indicate that the fiberglass bolts should be used as secondary supports due to the brittle nature of the material. Work remains to be done to get fiberglass properties nearer to those of steel.

Inorganic Grouts for Roof Bolts

Polyester resin roof bolts are relatively new to the mining industry. However, there are now about 20 million such bolts installed annually. Since resin cartridges are flammable, there is a potential underground fire hazard. To overcome this disadvantage, the Bureau began investigating substitute materials. Research showed that by combining gypsum-plaster with small microcapsules of water into a cartridge, roof bolting support characteristics similar to those of the organic grouted roof bolt resulted. This process has been patented and has been accepted and used in several foreign countries.

Uniformly Tensioned Roof Bolts

A mechanical roof bolt needs to carry tension before its presence is felt by the rock mass to be reinforced. Little or no tension allows rock movement. Rock movement tends to open cracks, thus suspending the strata and reducing roof stability. Mechanical roof bolts need to be installed with tension that is correct for the anchor and uniform with the adjacent roof bolts to insure good roof control. By controlling installation thrust, rotation speed, and torquing pressure at the drill head and by using hardened washers and lubricating the anchor threads, roof bolts can be installed with controlled tension.

The Bureau conducted a major field test of 15,200 expansion anchor bolts. One-fourth of the bolts were installed with equipment designed to insure uniform tension. Roof bolt tension was monitored on 2% of the bolt population. It was found that the average installed tension was 4,000 pounds for the conventional installation and 8,000 pounds for the controlled installation. A statistical analysis of the data showed three parameters to be particularly significant in correlation with roof sag: roof lithology, coefficient of variation of roof tension, and tension decay slope. The uniformly tensioned section achieved twice the uniformity of the conventional section as measured by the coefficient of variation. The roof sag in the uniform section was reduced by a factor of four. Results of the test indicated that (1) better bolt tension uniformity than is now customary can be achieved in practice and (2) improvements in bolt tension uniformity can result in improved roof stability. A manufacturer is now marketing a "full controlled bolting system."

Commercially viable improvements in the roof bolting process and roof bolting machines have resulted from many useful developments. A longer-than-seam-height (flexible) drill was developed and tested, self-drilling roof bolts

were investigated, an advanced bolter module for safer bolt installation was designed, a demonstration of roof bolter instrumentation for detecting hazardous roof was completed, remote manual roof bolters were designed, and faster bolting through improved bit design was demonstrated. To date, equipment suppliers and manufacturers have commercially adopted and developed only the flexible drill concept and the improved bit design information.

Flexible Roof Drill

The flexible roof drill has been under development for several years, but through Bureau efforts over the last few years, it is now being commercialized. The idea of the flexible drill is to allow roof support holes to be drilled in a confined space with the operator in a remote, safe location. This drill was particularly designed for roof bolting in low coal. The first commercial application is in American Borate Corp.'s Billy Mine in California. Additionally, Lake Shore, Inc., of Iron Mountain, MI, made a multimillion dollar commitment to commercialize this Bureau development.

OTHER ROOF SUPPORT SYSTEMS

Lightweight supports designed as substitutes for posts, crib blocks, and crossbars were identified, developed, and evaluated, some of which have been adopted by the U.S. mining industry. These included reinforced polyester resin, high-strength low-alloy steel, aluminum, and very high early-strength cement. Economic analysis indicated these lightweight substitutes were economically competitive in terms of life cycle costs. Other supports evaluated were a mobile shield, automated temporary roof support systems (fig. 28), a continuous miner-based automated roof support system, an aerostatic support system for use in underground auger mining, steel-fiber-reinforced concrete mine support members, and arch canopies. Most of these developments have been adopted by the mining industry and are employed in the day-to-day operations of many underground coal mines.

Arch Canopies

Rehabilitating a mine entry following a massive roof fall is extremely hazardous and poses a time-consuming, expensive problem for mine

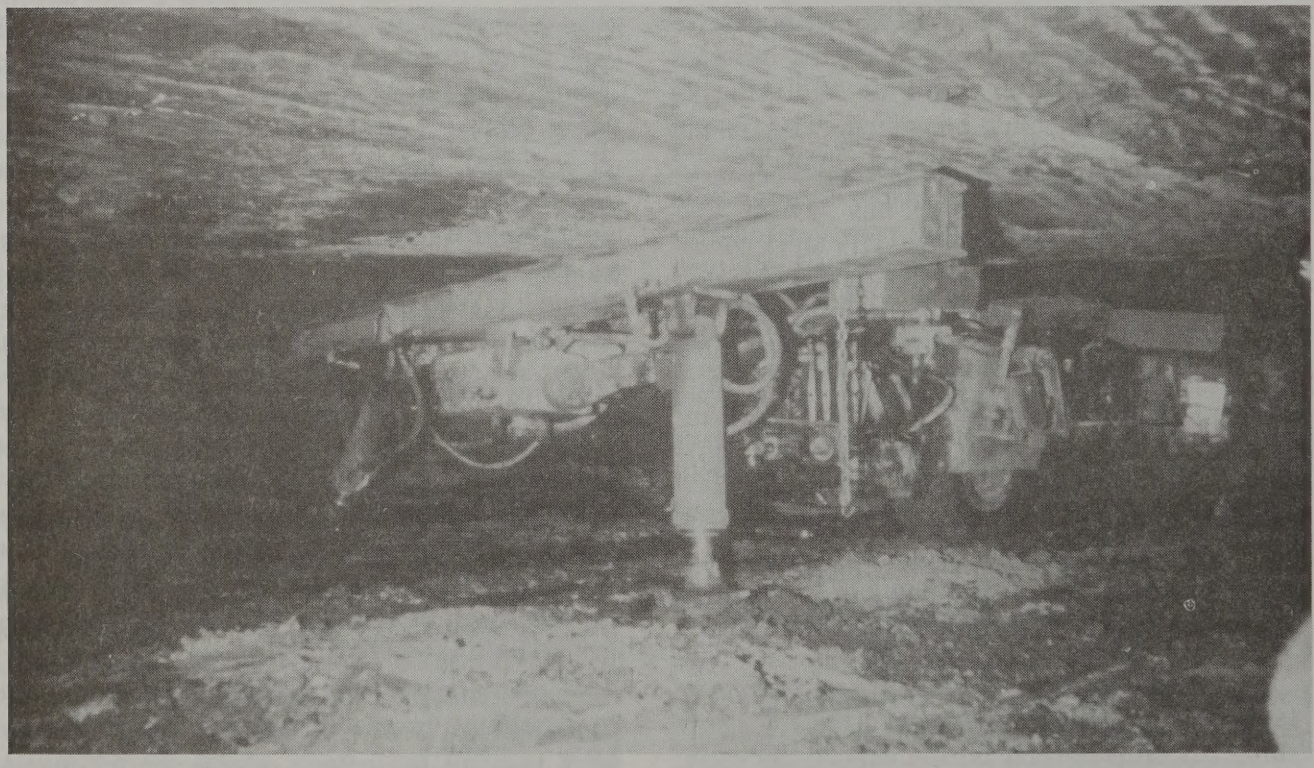


FIGURE 28. - The Bureau-designed automated temporary roof support eliminates the need for miners to work under unsupported roof.

management. From 1966 to 1986, 56 fatalities occurred while mine personnel were resupporting caved mine entries. In addition to the tragic loss of these lives, the monetary costs of fatal underground coal mining accidents are substantial: the average cost per fatal underground coal mining accident in 1989 was $1.1 million. Steel structures, predominantly arch canopies, have received considerable attention as a method for improving safety and efficiency when rehabilitating high-roof-fall areas. The function of the protective structure is to shield mine personnel from recurring roof falls, but not to stabilize and support the highly disturbed mine roof and ribs. The potential safety problem that arises with the use of these structures is that an improperly designed protective structure may collapse under the impact loading of a roof fall. The Bureau addressed these safety concerns by developing loading criteria and a design procedure for protective structures in 1987. Verification tests were conducted on arch canopies constructed of two- and four-flanged liner plate, and steel-sets and lagging. The tests showed that the design procedure is appropriate for these structures and yields conservative designs in terms of load-carrying and energy absorption capacities.

Lightweight Hydraulic Props (Posts)

Lightweight hydraulic supports (fig. 29) were developed by the Bureau to reduce back injuries to the miner and to make it easier and faster for miners to install temporary supports. These props weigh about one-half as much as any commercially available prop, yet carry the same load.

Yielding Steel Posts

A yielding steel post (fig. 30) was developed by the Bureau for underground mine support. There is a need in the mining industry for a high-capacity, thin-profile, yielding post support for use in roof areas where an excessive amount of mine entry closure is present. This 6- to 7-foot steel post was designed to yield nearly 2 feet while maintaining a 40- to 45-ton (force) load. The post is a three-piece unit consisting of top and bottom telescoping legs and a separate foot bracket. It develops its load-carrying characteristics when the lower

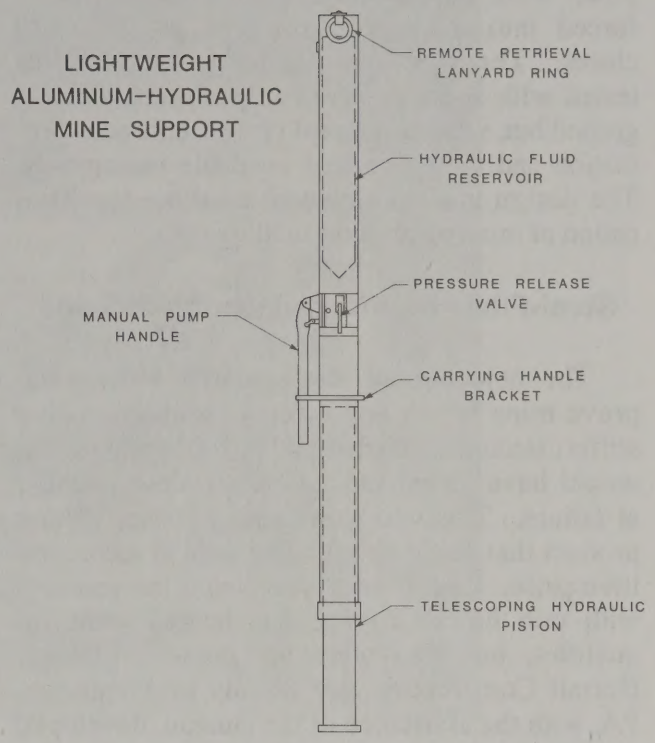


FIGURE 29. - Lightweight support design.

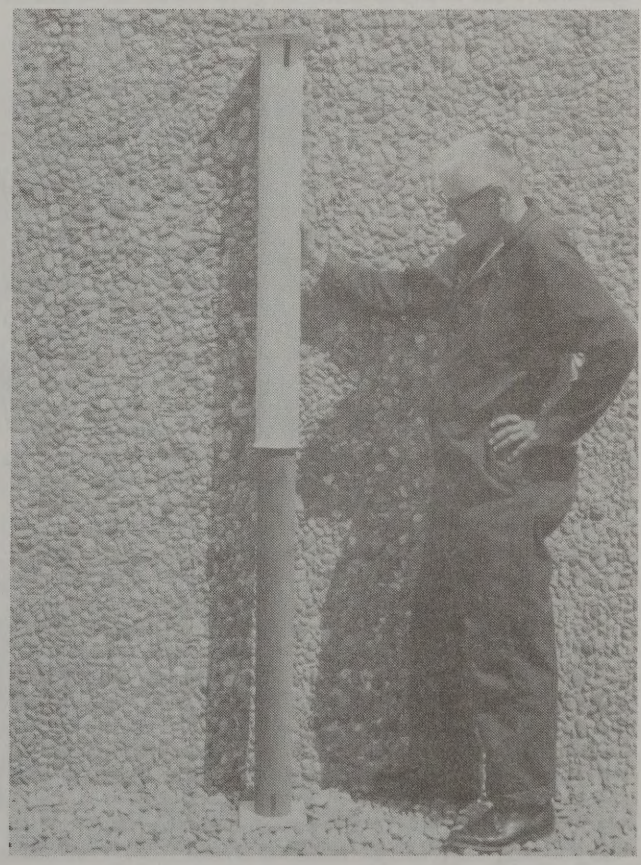


FIGURE 30. - Yielding steel post.

pipe, with an attached interference ring, is forced into the larger top pipe as the entry closes. The post was laboratory- and field-tested with success. It not only supports yielding ground but, with its reduced profile, enhances ventilation and the amount of available passageway. The design is simple enough to allow for fabrication at most mine shop facilities.

Steel-Fiber-Reinforced Concrete Cribs

The objective of this research was to improve mine health and safety conditions with a stiffer, stronger, nonflammable roof support that would have visual indications of slow yielding at failure. This was to be accomplished with a product that could be manufactured at a competitive price. The Bureau completed the research with crib blocks having the desired technical qualities, but they were not cost-competitive. Burrell Construction and Supply of Pittsburgh, PA, with the assistance of the Bureau, developed a method of mass producing these blocks at a competitive price. To date, more than 200 miles of these cribs have been installed in underground coal mines, with two to three additional mines undergoing installation each month.

CHEMICAL AND SEALANT ROOF REINFORCEMENT

Bureau research was instrumental in the adoption of both coal mine sealants and roof reinforcement by chemical injection. Several types of spray-on sealants were evaluated and shown to effectively stop coal and roof spalling. Various methods of chemical injection for roof rock stabilization used in foreign mines received the attention of the Bureau as their use began in U.S. coal mines.

LONGWALL MINING AND SHIELD DESIGN

The foremost developments involved the improvements in longwall mining, especially supports. Introduction of shields to the U.S. mining industry and the demonstration of lemniscate-type shields were engineered by the Bureau and adopted by industry. The Bureau designed and constructed a mine roof simulator for testing of longwall supports and supplemental support materials (fig. 31). The design and performance of longwall supports and supplemental support materials were greatly improved by the testing conducted in the mine roof simulator. Using the mine roof simulator's unique biaxial load frame to provide controlled load conditions, a detailed investigation of shield mechanics was made to evaluate how load is developed and transferred through the support structure. The understanding of shield mechanics resulted in: (1) identification of worst-case load conditions for each support component, (2) improved methodology for applying loads for performance testing, (3) methodologies to determine underground shield loading, and (4) determination of shield stiffness for application in numerical modeling and design considerations. Cooperative research with mining companies provided insight into shield failure mechanisms. From these studies, the Bureau developed recommendations for underground shield safety inspection and courses of action for common types of shield failures. Underground monitoring of shield loading has provided a data base from which models of support and strata interaction are being developed. The goal of these models is to optimize the selection and utilization of available shield capacity for various types of mine geologies. As part of this effort, the Bureau is investigating the influence of setting pressures on shield load development and strata control. The behavior of two-leg and four-leg shields has been determined from underground and laboratory studies, and practical considerations in their selection have been documented in several Bureau publications.

MOBILE ROOF SUPPORTS FOR RETREAT MINING

A Mobile Roof Support (fig. 32) has been developed to reduce or eliminate the hazard associated with a worker installing temporary or permanent roof support. With the assistance of a coal company in Utah, two Mobile Roof Supports were developed. Both machines are crawler-driven with four hydraulic support jacks, two of which are mounted on swing arms. In August 1984, this company reported that through 51 shifts no injuries had occurred, production averaged 947 tons per shift (normal pro-

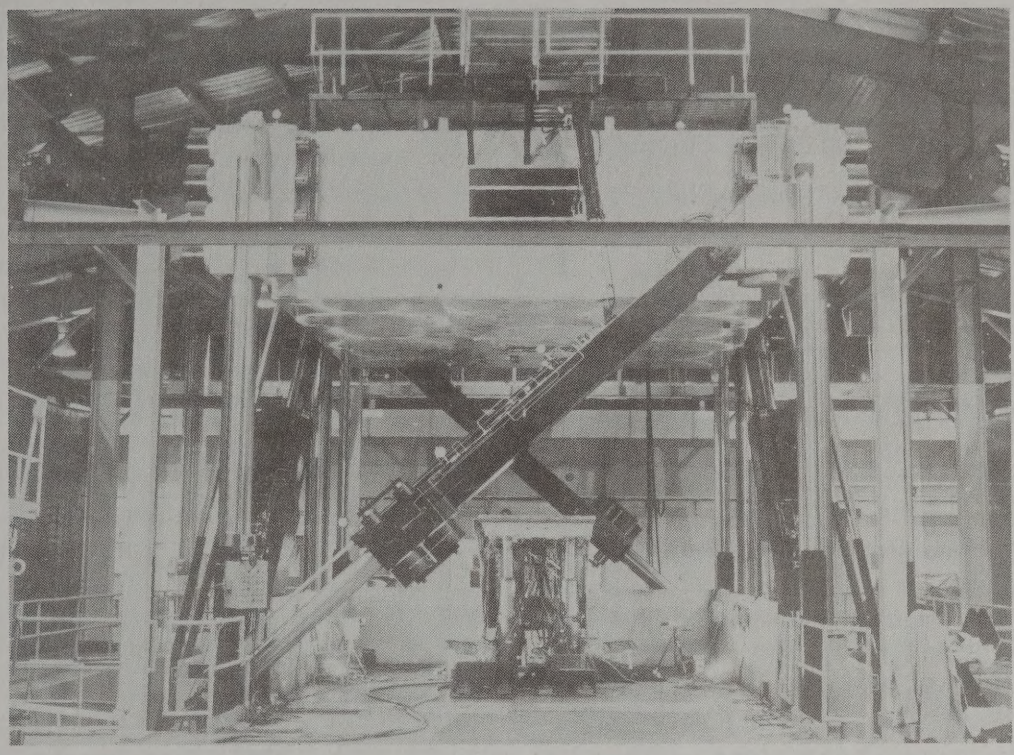


FIGURE 31. - The Bureau's mine roof simulator is capable of 3 million pounds of force for full-scale load tests of various roof supports and for studies of dynamic roof mechanics.

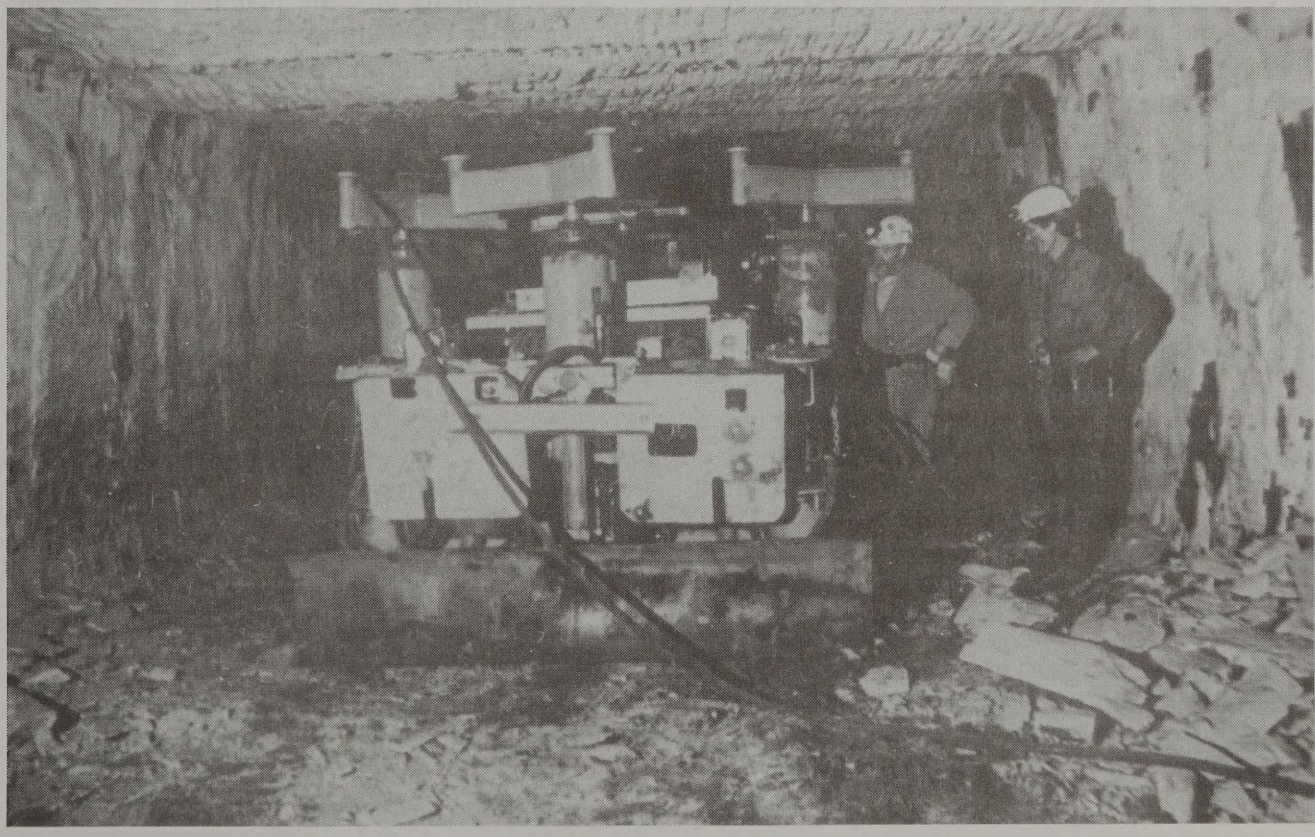


FIGURE 32. - Second-generation mobile roof support for use in underground retreat pillar mining.

duction was about 800 to 850 tons per shift), and 1,427 posts were salvaged.

The Mobile Roof Support system has been adopted by two mining manufacturing companies: Voest-Alpine AG of Austria and Fletcher Mining Equipment in the United States. The systems are similar, and both are now being used in U.S. coalfields.

AUTOMATED ROOF SUPPORT

Bureau of Mines work toward remote, automated, and robotics application in underground roof support started more than 15 years ago with the development of the roof bolt bender/inserter (RBI). Some mine seam heights are 24 inches or lower. Installing a bolt longer than the seam height requires manual bolt bending and re-straightening. The RBI bends a roof bolt from a horizontal orientation to vertical orientation while also inserting it into the bolthole. A more difficult task is the drilling of a long hole from a short seam height in confined space. Five different concepts were developed under Bureau contract. The RBI and the flexible drills have a limited market by themselves, but they are critical elements in remote, automated, and robotic mining equipment.

Developing an automated or remote drilling module is the first step toward developing a miner/bolter. A miner/bolter combines the functions of the continuous miner and a roof bolting machine and eliminates the cyclic nature of mining caused when withdrawing the miner to make room for the bolter. The safety feature of this type of operation is that the roof is supported almost as soon as it is exposed. The Bureau and the U.S. Department of Energy developed many different miner/bolter concepts. Both longer-than-seam-height and shorter-than-seam-height miner/bolters were built and demonstrated.

Several prototype semiautomated bolter concepts were completed and demonstrated. The objective was to move the operator to a safer location away from the drilling and bolting site while maintaining production. Although these first designs were not adopted by industry as practical, they did work and now form a solid base for renewed efforts by industry to develop automated bolter capability. Results of this work, along with instrumented "smart drill" technology developed over the past several years, are being combined in a program to develop an autonomous bolter capability by the late 1990's. The "smart drill" (fig. 33) is an instrumented roof drill that senses roof strata characteristics based on drilling parameters and relates these characteristics to optimum support required.

ONGOING RESEARCH

Past research efforts have led to the conclusion that to eliminate ground failures in underground coal mines, an understanding of the basic characteristics and factors causing the failures must be determined prior to implementing effective controls. This shift from development and demonstration to the present program of design-oriented research reflects the Bureau's commitment to basic research. The major areas of research now underway include multiple-seam mining, mountain bumps and rockbursts, pillar sizing, mine design, roof failure analysis, and rock mechanics.

Improvements in mine planning and design for control or elimination of the interaction effects accompanying multiple-seam mining have resulted from recent Bureau research (fig. 34). Both room-and-pillar and longwall mining of multiple coalbeds have been investigated, resulting in development of methodologies and techniques that allow for safe and economical extraction.

Coal mine pillar strength and pillar design studies and their application to longwall gate road design and room-and-pillar design have provided the mining industry with research results for optimal pillar design and safety when developing mine entries (fig. 35). Some of the specific studies include the Analysis of Longwall Pillar Stability (ALPS) coal pillar design method, yielding pillar studies, a computer program for mine design (MULSIM/BM), and studies of pillar stability in deep coalbeds, improved barrier pillar design, pillar stability in steeply pitching seams, and laboratory and in situ pillar strength.

FIGURE 33. - "Smart drill" in mudstone top collecting individual drilling parameter data at a mine near Price, UT.

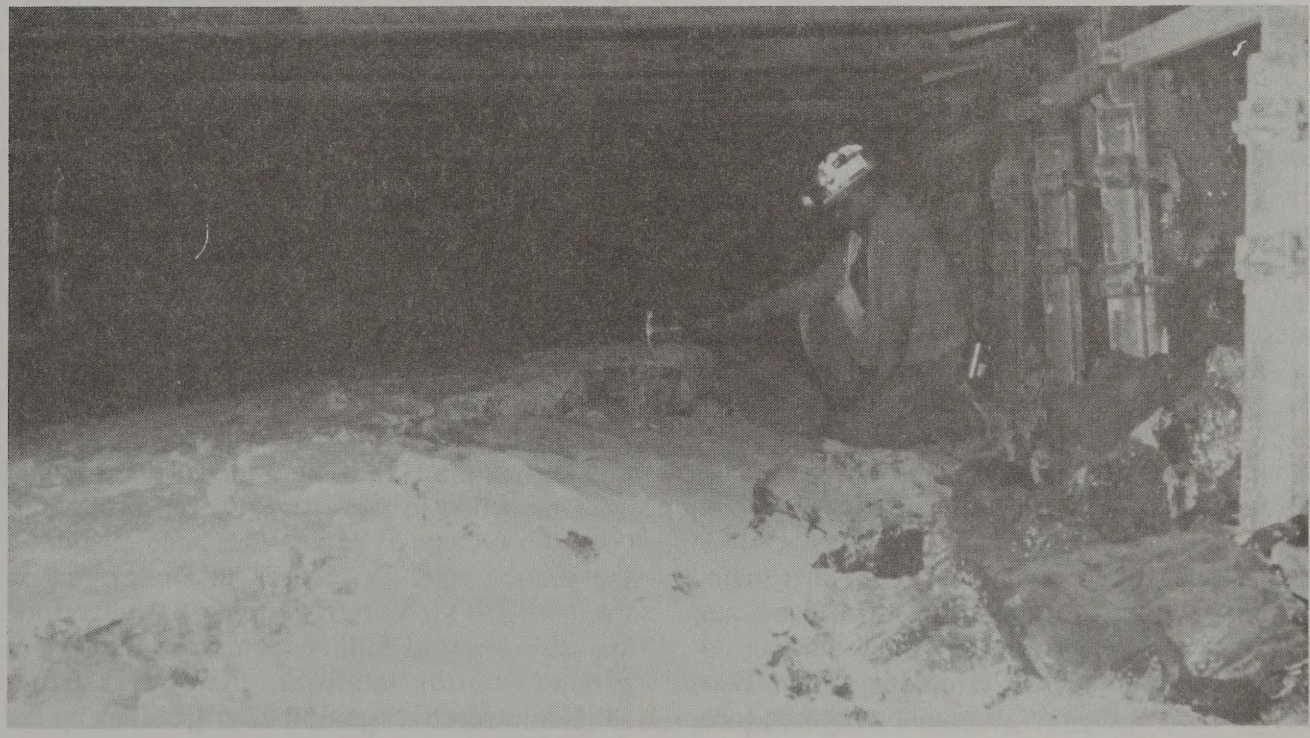


FIGURE 34. - Floor heave in a longwall gate road due to multiple-seam mining interactions.

FIGURE 35. - PC-based software is being developed to assist the mine operator in mine design.

Bureau research is developing innovative rock mechanics and pillar design approaches to solving mountain bump and rockburst problems (fig. 36). Research results are being used in mines experiencing bump and burst problems.

To meet the mining industry's need for improved field instrumentation, hardware and procedures were developed for determining the in situ state of stress, shear strength of coal and rock, coal and rock mechanical and physical properties, and bearing capacity of coal mine roof and floor. These techniques are commercially available for use by the mining industry. Additionally, blast design research is being conducted to reduce rock fall hazards by producing less fracturing and overbreak in the highwalls of open pits (fig. 37) and around underground openings. Emphasis is on low-cost techniques that are easily integrated into mine blasting operations with no adverse effects on safety. Blast design factors such as decoupling, charge location, and blasthole burden, spacing, and delay interval can have a significant influence on the damage to the perimeter of an opening. Specialized techniques such as presplitting along with air gap shooting reduced rock falls from a 175-foot highwall in a western U.S. coal strip mine. Blast designs developed by the Bureau to improve hanging wall stability and reduce ore dilution in vertical crater retreat stopes are now being used by Homestake Mining Co., Lead, SD. This Bureau blast design utilizes decoupled charges in a presplit-type blast in the row of blastholes that forms the hanging wall.

Owing in part to Bureau research accomplishments, the U.S. mining industry has seen a 76% reduction in total ground control fatalities (from an average of 85 fatalities annually during the years around 1970 to about 20 per year in the late 1980's). Current Bureau research efforts are attempting to further reduce the number of ground control fatalities, thereby assisting MSHA to reach its goal of zero fatalities by the year 2000.

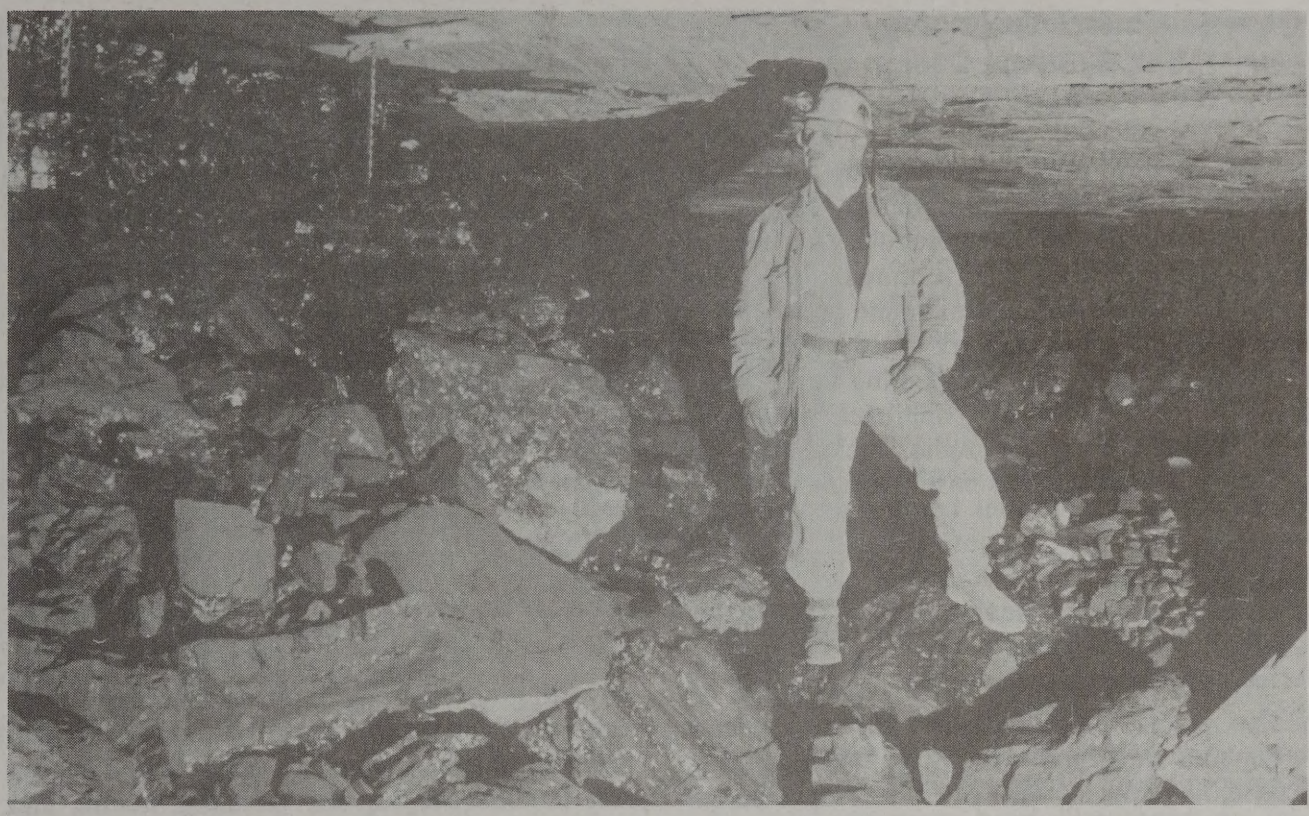


FIGURE 36. - Miner inspecting coal bump area in an eastern Kentucky coal mine.

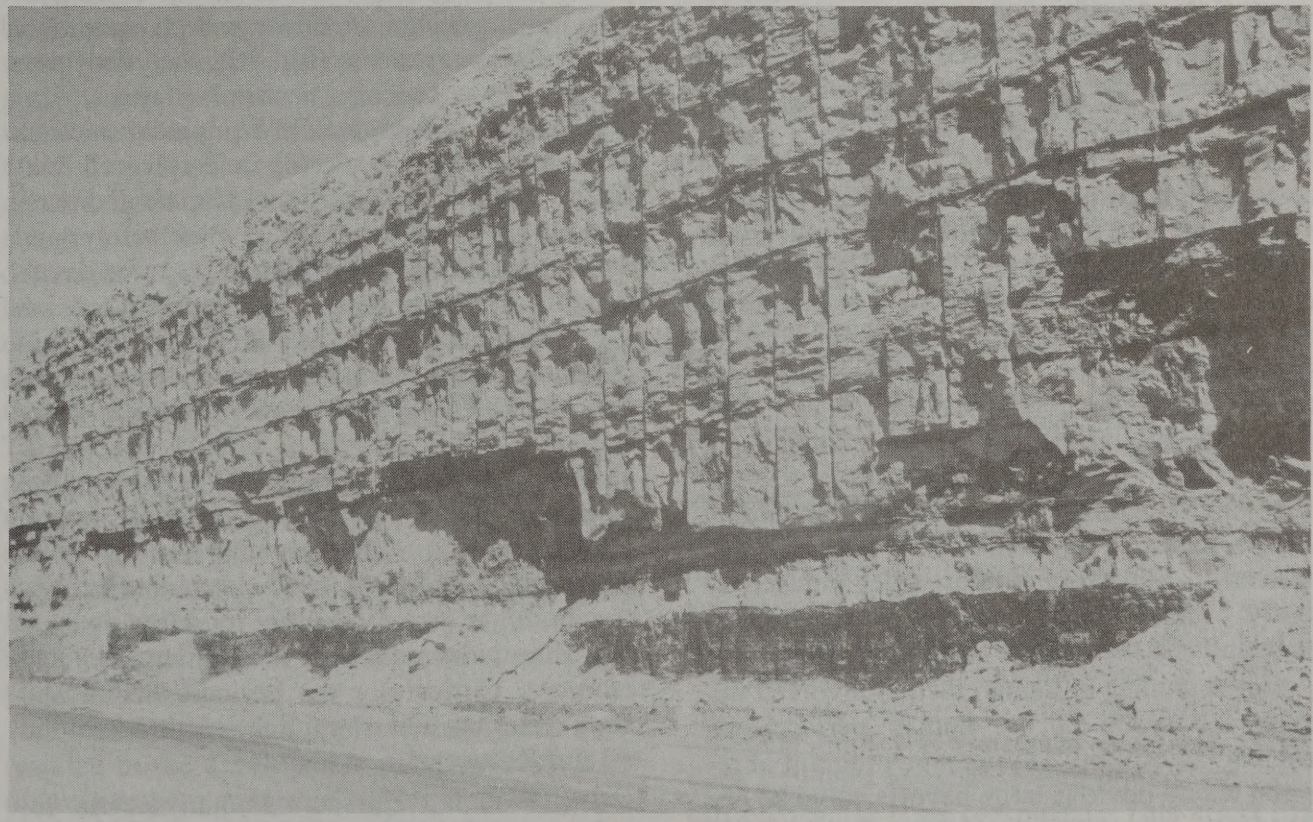


FIGURE 37. - The severe undercutting of this presplit highwall could be reduced by minor changes to the air gap blast design.

Generic Mineral Technology Center for Mine Systems Design and Ground Control

The Generic Mineral Technology Center for Mine Systems Design and Ground Control was established to further strengthen the cooperation and interaction between Government and academia in the areas of mine design and ground control. The Center's work focuses on the fundamental study of engineering designs as they apply to innovative approaches to coal mine extraction. These studies include a wide variety of topics, such as basic research on coal measure rock strengths, enhanced safety and productivity due to methane drainage, and cost-effectiveness evaluations of various roof support strategies. The research encompasses theoretical, laboratory, and in-mine studies. Most projects have application to virtually all underground mining operations. The Center's interdisciplinary activities entail the training of engineers and scientists, graduate students, and undergraduate students, as well as technology transfer to the mining community. The research programs complement the Bureau's in-house research studies on ground control and mine safety systems.

HUMAN FACTORS

Prior to 1969, the potential contribution of human factors research was not fully recognized throughout the mining industry. Mining systems and equipment were often developed based on tradition and production specifications, the role of management and supervisors was not well defined with respect to their safety and health responsibilities, and inadequacies in the training system, characterized by the notion that "experience is the best teacher," all combined to influence fatal and nonfatal injury rates.

With passage of the 1969 Act, research monies were significantly increased to accelerate the study of mining health and safety problems in mining. Research from 1970 to 1976 highlighted human error as a principal contributor to fatal and nonfatal injuries. Problems in human performance impact all mining activities, and the importance of human factors research was implicated through several research studies and expert opinion that suggest that 50% to 85% of all mining injuries are due in large part to human error. Research evidence also suggests that these errors in performance are often induced by poorly designed equipment, the work environment, and less than effective training programs.

Initial studies in human factors involved defining the scope of the human performance problem, developing a systematic program of research where obvious large payoffs could be obtained in the shortest period of time, and providing the mining industry and regulatory agencies with practical human factors research and development support. This resulted in several studies seeking to quantify health and safety issues such as (1) an assessment of health and safety training on injury frequency and severity rates; (2) human factors considerations in the design of underground equipment operator compartments (fig. 38), including provisions for seating, control layout, ingress/egress, and protective equipment such as canopies and panic bars; (3) field research linking the effect of organizational climate and management practices to issues of mine safety; and (4) research emphasis on human resource development, resulting in the development of job safety documentation (task analyses) that laid the foundation for improvements to instructional strategies and structured on-the-job training procedures.

This early research emphasizing attention to the human element was used in part for regulatory support in fulfilling the congressional mandate outlined under the 1977 Amendments Act. Among other items, the act required mining companies to increase their investment in human resources, particularly the periodic health and safety training and retraining of underground and surface miners.

In 1977, the Bureau's human factors research program was extended to include both

FIGURE 38. - Operator compartments with poor ergonomic design have caused hundreds of accidents annually. Operators must often lean out of the compartment owing to obstructed visibility from within the cab, subjecting themselves to possible injury.

basic and applied research, ranging from the ergonomic design of the mining workplace to projects that focused on personal and organizational variables. While the majority of work was of an applied nature, several studies addressed basic research problems. In the latter category are efforts that were directed toward determining physical work requirements for various underground mining tasks, computer modeling of the man-machine interface, and development of new methodologies for ascertaining machine operator visibility requirements. Three basic studies to identify human factors problems were completed addressing surface mining, underground coal, and underground metal and nonmetal mining. The product of each effort has served as source documentation for application of state-of-the-art solutions to identified problems or for recommending future research.

Applied research completed during this time resulted in the development of several new and innovative personal protective equipment items. New kneepads, new slip-resistant boots, and a new outer garment have been developed for the underground mining population. Numerous training packages were developed for the mining industry, several of which were initiated at the request of MSHA and served as a point of departure for mining companies to comply with the new regulations (30 CFR 48). Mine rescue training materials were researched, developed, and provided through MSHA to the mining industry. The development of these materials enabled industry to comply with the regulations specified in 30 CFR 48 and 49. Additionally, task training materials were researched and developed for surface mining operations, underground coal, and underground metal and nonmetal mining. These programs have been distributed to the mining community by MSHA and have found wide industry acceptance. During the same period, research was performed to improve on-the-job training procedures and methods by which miner training is delivered, and several training simulators were developed and successfully placed into operation.

Considerable work was also completed in the area of organizational development and personal variables associated with mine injuries. The effectiveness of reducing mining accidents through planned organizational change via the training of mine supervisors and managers has been demonstrated successfully in the field with two large mining companies; management and supervisory training materials for the underground coal mining industry have been developed; certification procedures for first-line supervisors have been thoroughly studied; and a supervisory training package for small mines has been developed and delivered to MSHA. Additionally, research to study the feasibility of utilizing employee assistance programs to reduce accidents associated with miners' personal difficulties has been completed. This effort has led some mining companies to initiate employee assistance programs. A program to determine

and demonstrate the effective elements of a model health and safety program for all types of mines has been completed and received favorable acceptance from MSHA and mining companies. Work also has been started to investigate the relationship between absenteeism and injuries and between the use of safety incentive programs and injury frequencies.

At present, the Bureau's research in human factors is focusing on (1) the design of operator compartments; (2) the redesign of underground mining tasks involving manual materials handling (fig. 39); (3) methods for disseminating human factors research information; (4) procedures for improving and evaluating training programs, particularly in the area of teaching miners judgment and decisionmaking skills when responding to underground mine emergencies; (5) basic and applied research in evaluating and teaching miners perceptual skills in the recognition of environmental hazards; and (6) the application of cost-benefit analyses to the implementation of human factors and training research.

Significant human factors research accomplishments to date have been realized in the following areas:

Applied research in defining methods for the teaching of nonroutine, mine emergency skills. Bureau-developed instructional methods and materials are impacting the conduct of health and safety training within and outside of mining. Other industries are beginning to use health and safety materials researched and developed by the Bureau. Field testing and publication of 55 latent-image and role-playing exercises for use in teaching and assessing miners' judgment and decisionmaking skills in the event of a mine emergency have been completed. These materials are highly regarded as being authentic, challenging, and useful in the instruction of nonroutine mine emergency skills. Industry experts and labor leaders have voiced high regard for these products and view them as a major innovation in mine health and safety training.

Criteria to assess the effectiveness of health and safety training, including the design of innovative teaching and assessment strategies. These instructional procedures will help miners respond to the large variety of rare but critical mine emergency situations, ranging from the treatment of injured victims to dealing with underground mine fires and explosions.

Broad distribution of health and safety training materials through MSHA's National Mine Health and Safety Academy, Beckley, WV. Recent Bureau developments in materials used for conducting annual retraining resulted in numerous requests by mining companies and the dissemination of thousands of copies of these materials by MSHA.

Demographics. The most complete analysis to date of the demographics of the U.S. mineworker population has been completed as it pertains to the status of the mining industry worker population for the year 1986. Demographic statistics were developed using population sample survey methodology for six mining industry sectors: coal, metal and nonmetal, metal only, nonmetal only, stone, and sand and gravel. Bureau Information Circulars detailing demographic results for each of these sectors have been published. These results include a description of the population characteristics and distribution for such variables as age, gender, overall mining experience, experience at present company, job category, and geographic locale. The demographic findings also were related to safety statistics for the 1986 mineworker population. Among the conclusions supported by the findings are: (1) the injury rate for inexperienced mineworkers is higher than that for experienced mineworkers, regardless of age; (2) among all industrial sectors, back injury risk is highest for mobile equipment operators in the coal industry; and (3) back injury risk is highest for mineworkers in the 30 to 39 age group and lowest for workers in the over-50 age group.

Mobile Mine Equipment Maintenance Safety. Maintenance activities are responsible for between one-fourth and one-half of both the costs and the accidents associated with mining operations in the United States. Maintenance safety research is aimed at addressing this general problem area, particularly in relation to mobile equipment maintenance operations. One analysis identified three haulage truck systems that are the most hazardous to maintain, namely, the cooling, suspension, and tire systems. A subsequent analysis of risk factors contributing to surface mine maintenance slip-and-fall accidents revealed that the highest risk of such acci-

FIGURE 39. - The stresses of manual materials handling and the redesign of underground mining tasks have been researched by the Bureau of Mines under its human factors program.

dents is associated with maintenance worker interaction with access system elements, such as ladders, steps and stairs, and walkways.

Failure to follow proper procedures represents the third most prominent cause of maintenance accidents. More recent research with this project, therefore, has addressed the question of how maintenance workers interact with service and repair manuals. The ultimate objective is to improve the ability of maintenance workers to read and comprehend the information provided. Comparisons have been made between various formats of written and computerized manuals. The results suggest that improving the readability and layout of a maintenance manual can benefit performance of mine maintenance work. However, use of a computerized maintenance information system is likely to benefit perfor-

mance only if the system is designed to be compatible with the specific operational characteristics of mine maintenance work.

Vigilance Tasks and Safety. Many tasks in mining require a sustained level of operator vigilance (attention) during task execution. One prominent example is mobile equipment operation. A number of factors may compromise driver alertness during operation of mobile mining equipment. These include the repetitive nature of the task (as in surface haulage activities), distraction due to noise or vibration, fatigue, or sleepiness during night shift operations. Impaired operator alertness associated with the performance of vigilance tasks continues to constitute a problem for the mining industry, particularly as equipment has become larger and more complex, and equipment accidents consequently have become more serious and costly. Research aimed at assessing the accident risk associated with vigilance tasks in mining was initiated to address this problem area. Analysis shows that mineworkers engaged in high-vigilance tasks, particularly mobile equipment operation, experience accidents that are two to three times more severe than those experienced by mineworkers engaged in low-vigilance tasks. A related finding from shiftwork research (discussed below) is that accidents experienced by mobile equipment operators during night shift are more severe than those experienced by operators on day or afternoon shift. Consequently, current work is focusing on shiftwork generally, and night shiftwork in particular, as a major contributor to alertness problems confronting operators engaged in high-vigilance tasks in mining.

Shiftwork. Owing to the high cost of mining machinery, many companies require 24-hour operations. Previous research has shown that working nights and shiftwork in mining and other industries has been correlated with accidents, sleep deficiencies, decreases in performance, fatigue, gastrointestinal disorders, cardiovascular disorders, absenteeism, lowered morale, and social and marital problems. The purpose of this research, therefore, has been to develop recommendations for improved shift rotation designs and individual coping mechanisms that can improve the safety and health of miners. An analysis of 6,546 surface mining accidents during a 10-year period indicated that accidents are not simply a function of fatigue due to time on shift, but rather a complex interrelation of time of day, the particular shift worked, day of week, and age. With a better understanding of these variables, some schedules or schedule components are more conducive to adjustment considerations. Other experimental studies have shown that (1) 2-week rotation schedules are preferable to 1-week schedules; (2) the direction of rotation, forward or backward, has little effect on adjustment to the schedule; (3) "earlier" work start times have a positive effect on working the night shift; (4) "delaying" sleep after a night shift is related to frequency of some health complaints, while "early" sleep times are related to increased fatigue at work; and (5) older workers experience more difficulties on the night shift. Training modules are being developed to teach coping strategies to shiftworkers. Current research is focused on safety and health concerns of working extended days, such as 10 or 12 hours.

INDUSTRIAL SAFETY

MINE MONITORING

The objective of the environmental monitoring program was to increase mine safety by providing mine management with continuously updated information on underground conditions so that early corrective action could be taken before hazardous situations developed. The focus of this program, however, changed three times from 1974 to 1984 as industry needs changed and technology advanced.

From 1974 to 1979, the feasibility of continuous environmental mine monitoring was pursued. Transducers were developed and evaluated for the measurement of methane, carbon monoxide, and air velocity. Intrinsic safety, lack of specificity to the parameter of interest, and durability of monitoring equipment in the mine environment were addressed to allow for

underground installations. Techniques were evaluated for bringing information to the surface from underground locations, including hard-wired, tube-bundle, and telemetry. Various transducer and system configurations were evaluated in coal and metal/nonmetal mines. The feasibility of monitoring in U.S. mines was demonstrated, and an interest was generated in the industry to develop commercial monitoring systems for mine use. Mine monitoring began to be seen as a way to provide increased safety for mineworkers.

In 1979, a major deficiency of existing monitoring systems was identified—their reliance on mine electrical distribution systems for power. It was recognized that if the system is to be useful and reliable under emergency conditions, all equipment used must be intrinsically safe. A totally intrinsically safe mine monitoring system was developed and installed at Rochester & Pittsburgh Coal Co.'s Lucerne No. 8 Mine, where it operated with favorable results.

By 1983, the basic technology for mine monitoring systems was reasonably well developed, and the mining industry had begun to accept them. Approximately 38 systems were installed in U.S. underground mines, and 12 manufacturers were selling monitoring systems. Research then refocused on system-user interfaces, management information systems (fig. 40) to assist mining companies in managing the information from mine monitoring systems, and equipment monitoring and control.

The Bureau entered into a cooperative agreement in 1982 with Western Fuels Association, Inc., to evaluate cost/benefits and performance of a comprehensive monitoring, control, and management information system at its Deserado Mine. The system monitored more than 700 points, including face equipment, environmental conditions, fire sensors along the belts, and monitored and controlled belt conveyors. Under this cooperative agreement, the installation and operation of the monitoring system installed at the Deserado Mine were evaluated over a 2-year period. Safety benefits resulted from having a continuous readout of the environmental conditions throughout the mine at a surface location where control of conditions could be coordinated, as well as the availability of data for increased preventive maintenance of equipment and the optimization of equipment use. Production benefits resulted in turn from increased conveyor belt availability. The experience of the Deserado Mine in purchasing, installing, and operating a mine monitoring system for a large-

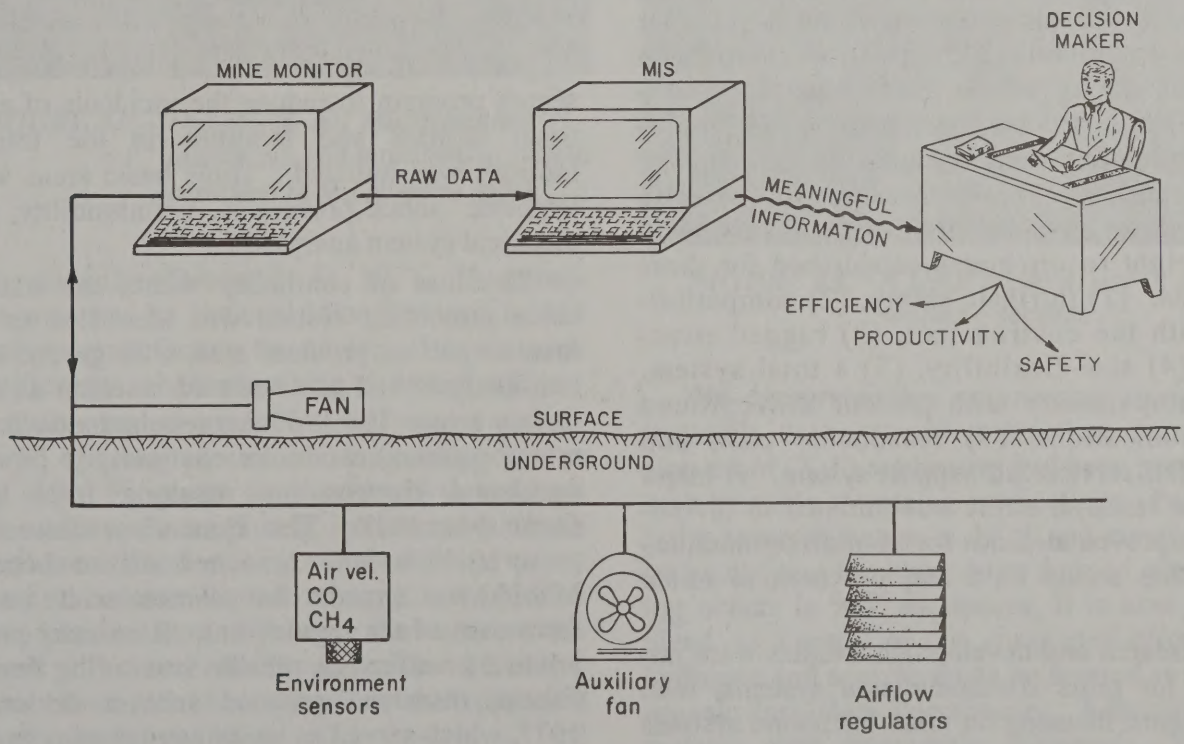


FIGURE 40. - Mine management information system.

scale mine complex was documented in a report to benefit other mine operators considering the purchase of a monitoring system for their mines.

Bureau research has had a direct impact on the progress of mine monitoring to where it is today, with approximately 100 underground coal mines having monitoring systems installed and 10 manufacturers marketing systems to the industry. Under the mine monitoring research program, sensors were developed, telemetry systems were evaluated, a totally intrinsically safe mine monitoring system was developed, recommendations to increase the reliability of systems were specified, and test criteria and an apparatus for the evaluation of mine monitoring systems were developed. The technology from this program was successfully transferred to MSHA and the mining industry through technical briefings at conferences and Bureau-sponsored industry seminars, as well as published reports. As a result of this technology transfer effort, manufacturers incorporated Bureau technology into their products, and mining companies gained interest in mine monitoring and became aware of the benefits that it could provide their operations.

COMMUNICATIONS

The 1969 Act called for the availability of a system to communicate both on the surface and underground. There was no problem in communicating on the surface with conventional radio systems, but upon entering a portal or going underground, a system of communication was necessary. In the early 1970's, the overall problem was assessed, with eight requirements established for these systems: (1) intrinsic safety, (2) compatibility with the environment, (3) rugged structure, (4) size flexibility, (5) a total system, (6) compatibility with present aboveground communications, (7) reasonable cost, and (8) a full service-full support system. A major Bureau research effort was initiated to investigate improved methods for in-mine communications that would be a major benefit to miner safety.

Research and development studies were initiated for mine communication systems, with early work focusing on mine telephone systems such as pager phones and carrier phones. Innovative additions to these systems included electromagnetic and visual paging, so that a person did not actually have to be near a telephone to know that an incoming message had arrived. Advanced research on telephone systems included multichannel capability and inclusion of mine monitoring (figs. 41-42).

Additional work focused on ultra-high-frequency (UHF) radio systems (fig. 43) and medium-frequency quasi-radio systems that are now used in underground mines. These systems provided true radio coverage to roving miners who no longer had to be near a fixed telephone to communicate. Modifications of these techniques also provided methods for communicating in hoist shafts and under mine emergency conditions.

The technology evolving from the Bureau's in-house and contract efforts has been incorporated by manufacturers into their own product lines. UHF systems are offered by Motorola; the dedicated wire technique for rail haulage is the basis for systems offered by Mine Safety Appliances Co., National Mine Service Co., and Comtrol; and A.R.F. and Stolar, Inc., offer commercial products based on the whole-mine medium-frequency communication system.

ELECTRICAL HEALTH AND SAFETY RESEARCH

As a result of the 1969 Act, an electrical research program to reduce the incidents of electrical injuries and fatalities in the mining industry was initiated. Three basic areas were targeted: shock prevention, permissibility, and electrical system analysis.

The loss of continuity within the trailing cable grounding system was identified as the most important problem area, with ground system analysis and cable-related research as secondary areas. The 1969 Act required a device to monitor ground conductor continuity to prevent accidental electrocution resulting from high frame potentials. The Bureau's enforcement group (which later branched off to become MSHA) was forced to issue a moratorium on enforcement of the regulation until industry could produce an effective, reliable monitoring device. Bureau research produced such a device in 1977, which served as an industry prototype and enabled MSHA to enforce the ground check moni-

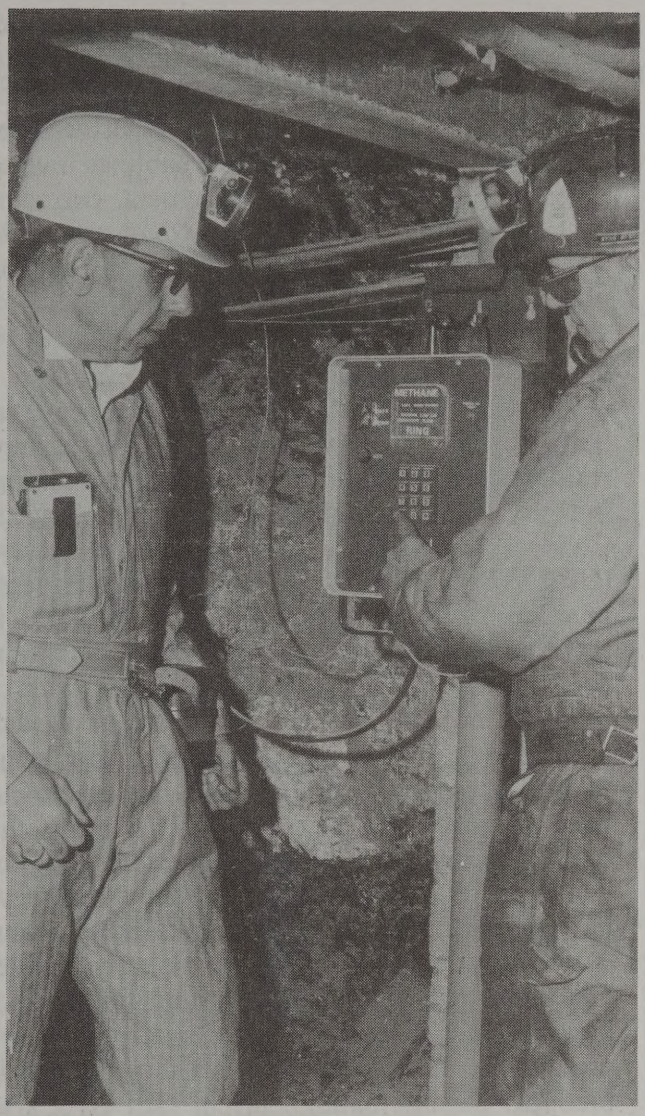


FIGURE 41. - The MCM-101 multichannel telephone and monitoring system installed in the Robena Mine.

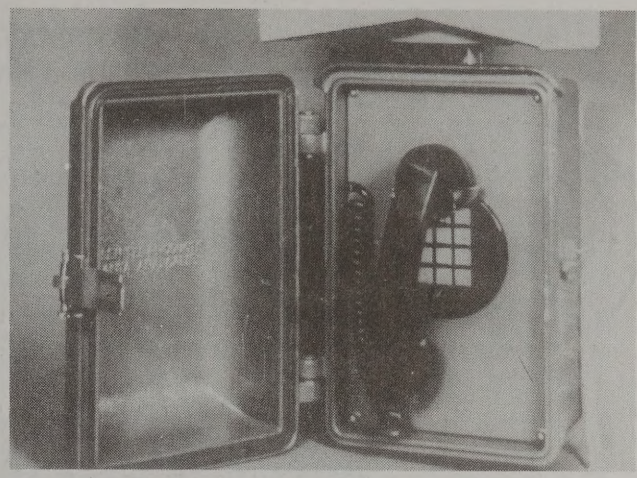


FIGURE 42. - The carrier current multiplexed telephone system developed for the Sunshine Mine.

FIGURE 43. - A UHF radio in use in a working section.

tor statute after December 31, 1977. The prototype was used by National Mine Service Co. and others to manufacture the device. This research significantly enhanced mining electrical safety.

Cable-related research concentrated on improved splicing procedures for trailing cables (fig. 44). Programs were initiated to redesign splice kits to better protect spliced cables from short circuits and moisture intrusion and to increase their mechanical strength. Improved crimp connectors and joining sleeves were designed. The end of this effort saw 12 major splice kit manufacturers improve their products based upon Bureau work.

No comprehensive engineering analysis of materials or construction practices for explosion-proof (X-P) enclosures had been performed with attention to mining applications. Permissibility research began in 1976 and concentrated on identifying the byproducts formed when arcing occurs in X-P enclosures. It is now recognized, as a result of this completed effort, that hydrogen and acetylene can be formed as certain organic insulators decompose. Adhesives and sealants were thoroughly evaluated. The research produced an acceptance criterion for use

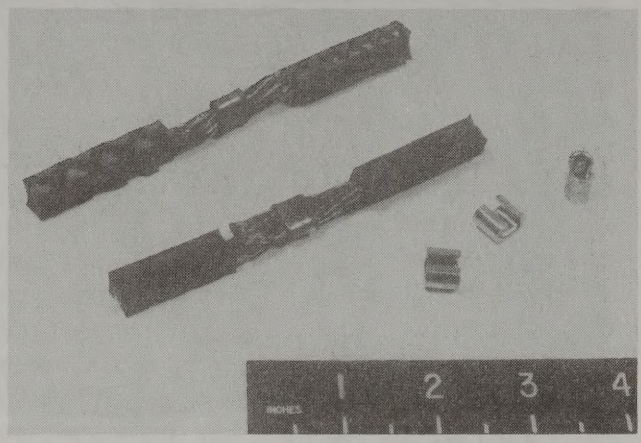


FIGURE 44. - Bureau research has focused on improved splicing procedures for trailing cables.

by MSHA in evaluating new adhesive/sealant materials. Research into X-P enclosure design led to the development of a novel venting structure to allow manufacturers to reduce the weight of enclosures without sacrificing X-P performance. This same research also demonstrated a quick opening cover concept and an asbestos rope substitute packing gland.

Intrinsic safety concentrated on basic research into ignition mechanisms. Factors influencing the minimum igniting current level were identified. Beginning in 1980, resources were committed to the design of an intrinsically safe power supply based on the principle of rapid load current termination. A thoroughly tested, intrinsically safe supply was subsequently awarded a U.S. patent. This effort supported the minewide monitoring program.

No detailed information existed on mine power system design or performance. Generally, underground mine electrical systems had been excluded from detailed surveys on reliability and performance, probably because they are not covered by the National Electrical Code. Little was known about mine grounding systems with respect to their overall performance. In an effort to address the requirement under 30 CFR 75 for low-resistance grounding mediums for mines, the Bureau undertook research to systematize the design of ground beds based upon soil and other environmental conditions (such as rainfall and altitude) so that mining companies could maintain compliance with the 5-ohm bed resistance requirement. This research led to the publication of Information Circular 8767, which greatly simplified the design of driven rod ground beds. Other ground bed subjects investigated were ground bed measurement, corrosion of ground rods, and composite bed materials. After 1980, bed design could be reliably accomplished, and emphasis shifted to analysis of shock potentials from equipment located remotely from the ground bed.

Ground fault interrupting devices are required by the National Electric Code in all new residential construction. However, the mining industry is not bound by the National Electric Code and was slow to adopt ground fault relays (GFR's) because of the high power requirements of mine machinery. In residences, the GFR is required to protect a 15-ampere (A) branch circuit and trip the circuit when a ground fault of 0.005 A occurs. Typical mine power system ground fault current protection levels are in the 5- to 7-A range, about 100 times the electrocution threshold for humans. In mining, the 0.005-A limit is not achievable because the protected circuit may be required to supply 1,000 A or more during startup of machines like continuous miners and longwalls. Additionally, the device must not trip when a ground fault is not present, since that would unnecessarily interrupt production. Bureau research has shown that it is practical for alternating current (ac) GFR's to trip at 0.050 A and direct current (dc) GFR's to trip at 0.150 A on mine power circuits without excessive false tripping. In 1984, Bureau electrical research produced an ac GFR with a protection sensitivity of 50 milliamperes (mA) designed for use on electrically powered mobile mine equipment (fig. 45). Mineworthy prototypes were constructed by FEMCO of High Point, NC. In 1986, a dc GFR was developed that provided electrocution protection at 150 mA on dc mine circuits.

A detailed study of cables and related accidents also recommended development of shielded low-voltage trailing cables. Conventional metallic braided shields were found to be too inflexible for use in reeled applications, for they deteriorated rapidly under repeated flexing. The Bureau developed, through The Pennsylvania State University and the British Industrial Cable Corp., a flat, conductive rubber-shielded

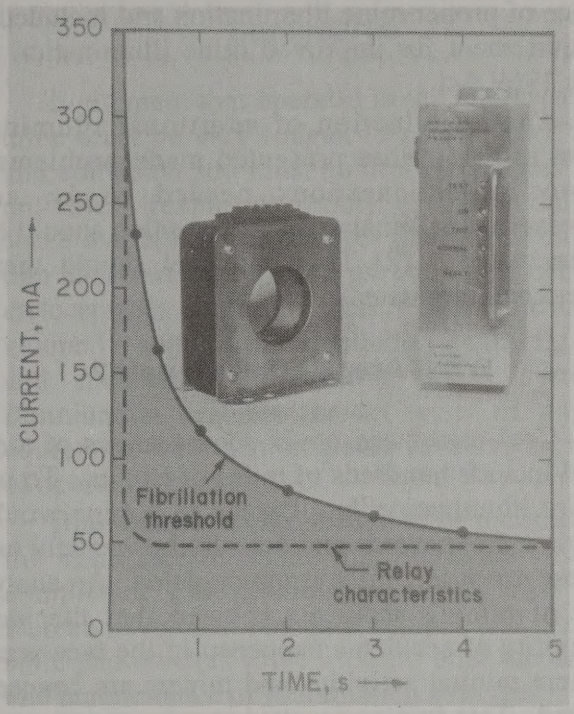


FIGURE 45. - Bureau electrical research produced an ac ground fault relay with a protection sensitivity of 50 mA designed for use on electrically powered mobile mine equipment.

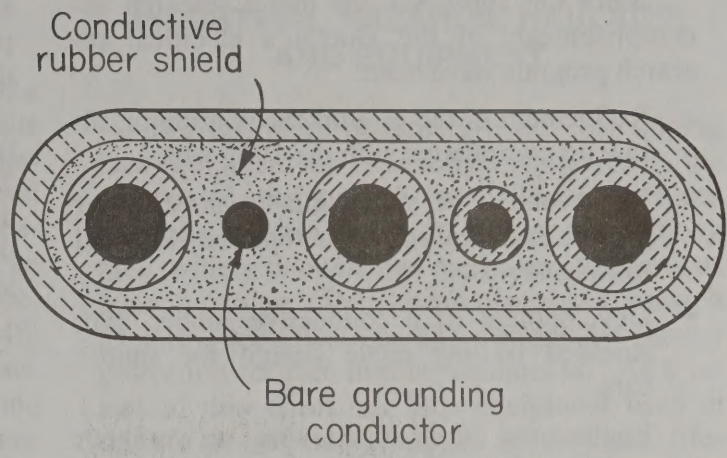


FIGURE 46. - Conductive rubber-shielded trailing cable.

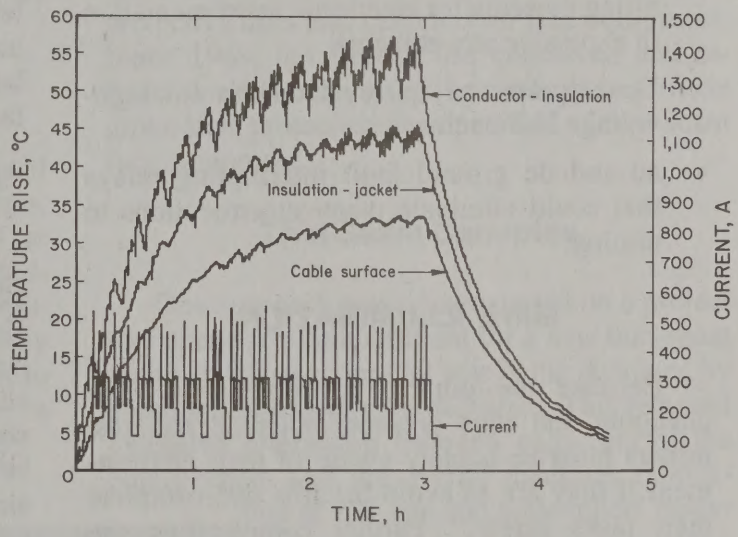


FIGURE 47. - Trailing cable current carrying capacity.

cable design for shuttle cars that provided not only the protection of a shield, but also cable flexibility almost equal to that of an unshielded cable (fig. 46). Proposed new MSHA regulations would require greater electrocution protection for miners and may require the use of Bureau-developed shielded cables, as well as sensitive ground fault protection devices.

In 1983, X-P enclosure research produced a detailed finite element analysis of X-P enclosures, extensive thermal analysis, and analysis of X-P windows and lenses. Performance-based design recommendations for X-P enclosures have also been published.

Research begun in 1984 examined MSHA's allowable current carrying capacity (ampacity) for low-voltage trailing cables used in underground coal mines (fig. 47). It established that the present 30 CFR 18 ratings are from 16% to 25% too conservative for trailing cables that never exceed their average 90° C insulation ratings. For situations where cables are permitted to exceed 90° C, the allowable ampacity ratings could be even higher. The practical effect of this research will be to allow approximately one smaller standard cable size to be used on machines employing trailing cables.

In addition to reducing the incidence of back injuries when handling heavy cables and the consequent compensation payments for these injuries, this research offers a profound benefit to industry in the form of savings that result from buying smaller cables.

Since the 1969 Act, the major research accomplishments of the Bureau's electrical research program have been:

- Refinement of the ground check monitor, allowing compliance with the 1969 Act.
- Improvement of splice kits to provide for greater electrical safety on repaired electrical trailing cables.
- Development of a conductive rubber, flat, shielded trailing cable design for shuttle cars.
- Engineering analysis allowing an in-depth understanding of the dynamic performance of X-P enclosures.
- Development of a procedure to design mine ground beds.
- Statistical characterization of minimum igniting currents for electronic instrumentation in explosive atmospheres.
- Development of approval criteria for high-voltage X-P enclosures.
- ac and dc ground fault interrupting relays that could eliminate many electrocutions in mining.

MINE ILLUMINATION

Because the mining environment is ever changing and thus presents potential hazards, miners must be acutely aware of their environment if they are to avoid hazards and complete their tasks safely. Further complicating the miner's work is the fact that the mining environment is dark, and humans obtain the vast majority of their information about the world around them through their eyes. Historically, limited underground lighting and visibility have contributed to the hazards of the worksite.

In the 1960's, miners relied on the cap lamp as the sole source of illumination while underground. While the cap lamp was a vast improvement over the carbide and flame safety lamps of the past, it provided only a limited spot of light, effectively eliminating peripheral vision. The U.S. Congress recognized the importance of proper mine illumination and included a requirement for improved mine illumination in the 1969 Act.

The introduction of additional illumination in coal mines presented many problems. Two initial questions needed to be addressed: (1) What areas of the mine should be illuminated? (2) To what level should these areas be illuminated?

What Areas To Illuminate?

Coal mines can cover square mines of area and include hundreds of miles of entries. To require illumination in all areas of a mine would impose fire hazards and actually be wasteful because much of a mine is unpopulated. An analysis of mining accidents showed that the vast majority of accidents happened in the face area, where mining activities and miners are concentrated. This finding resulted in subsequent regulations that required the illumination of the face area.

What Level of Illumination Is Needed?

Illumination requirements for factories and other general worksites had long been defined. However, these requirements were developed to optimize human performance, not to insure the ability to detect hazards. Additionally, prior work assumed that the entire workplace would be illuminated to the same level. To impose similar standards in the mining environment would result in adaption problems when miners had to move from bright to dark areas. Also, the confined space and dark walls of a coal tunnel would require very bright and compact lighting fixtures that would cause severe glare problems. Thus, the Bureau conducted research to determine the minimum light level required to insure a safe workplace. This level, 0.06 footlamberts, is just above the amount of light needed to cause the human eye to operate in "day vision" mode and at the approximate level provided by the miner's cap lamp. Thus, adaption problems, glare, and cost of compliance were minimized while safety performance was optimized.

Luminaires

Equipment that operates in the face area of a mine must be very rugged to survive roof falls and collisions and must be designed to be "permissible" (explosion-proof). The confined space available also requires that any illumination hardware be very compact and yet not be an unacceptable source of glare. The Bureau developed a suite of illumination systems (fig. 48) and methods for installing those systems. Illumination systems for all types of mining equipment were demonstrated in active sections of operating coal mines.

Illumination levels needed to be measured at the mine face to insure that machines were in compliance with promulgated regulations. The Bureau developed compact, rugged, and permissible photometers to be used for both the design and maintenance of illumination systems.

Impact

All face equipment used in today's coal mines includes permissible illumination systems, and miners now enjoy improved visibility in those areas of the mine that are the most hazardous. Mining companies and equipment manufacturers have a number of commercially available illumination systems to draw upon to meet MSHA standards that have become a model for the entire world mining community.

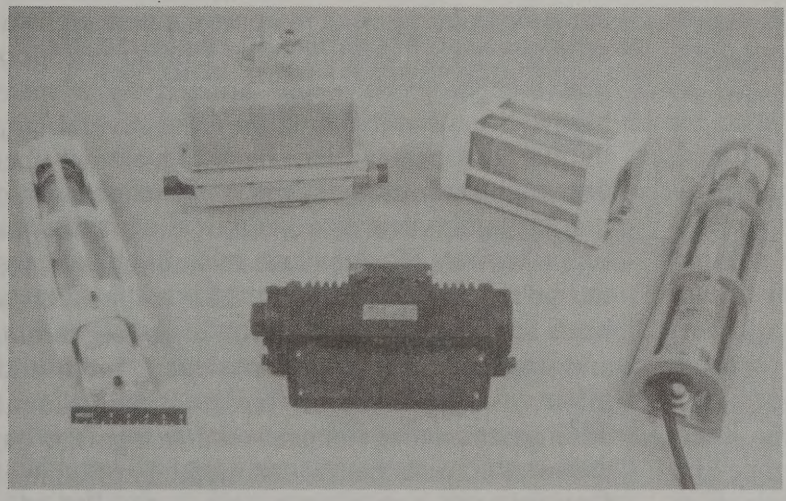


FIGURE 48. - Bureau research led to the development of a suite of illumination systems to improve visibility in the hazardous underground environment.

INDUSTRIAL HAZARDS, HAULAGE, AND EQUIPMENT

The operators of underground coal mining face equipment are especially endangered by the ravages of roof and rib falls. These machines normally operate within 25 feet of the working face, widely documented as the most hazardous zone in mining. The Bureau completed research to define specifications and designs for canopy protection on face mining equipment. As a result of this effort, all face equipment used in thicker seams are equipped with these life-saving devices. Cabs and canopies have established an impressive record of protecting operators, with hundreds of saved lives and avoided injuries documented. However, vertical space constraints imposed by thin seams make it extremely difficult, or impossible, to provide protective cabs and canopies on face equipment. Since 1969, the Bureau has conceived and refined two different, effective methods to provide groundfall protection for operators of thin-seam face equipment.

Thin-Seam Canopies

One approach was demonstrated on a protective operator's compartment for a new thin-seam mobile bridge carrier that was being designed by a major equipment manufacturer. This required extensive interaction between engineers of the compartment and the overall machine, fabrication of full-size and scale-model mockups, utilization of many innovative compartment design ideas, and thorough surface and field testing. A protective operator compartment resulted that became available as a standard option on the Jeffrey MMD Model 5010 bridge carrier (fig. 49). The bridge carrier with compartment has proved usable in seams as low as 40 inches. A total of 52 Model 5010 bridge carriers are currently in operation in coal mines, with 50 of the units equipped with the operator's compartment. The mining industry's use of this Bureau development has certainly prevented operator injury and has served as an example of suc-

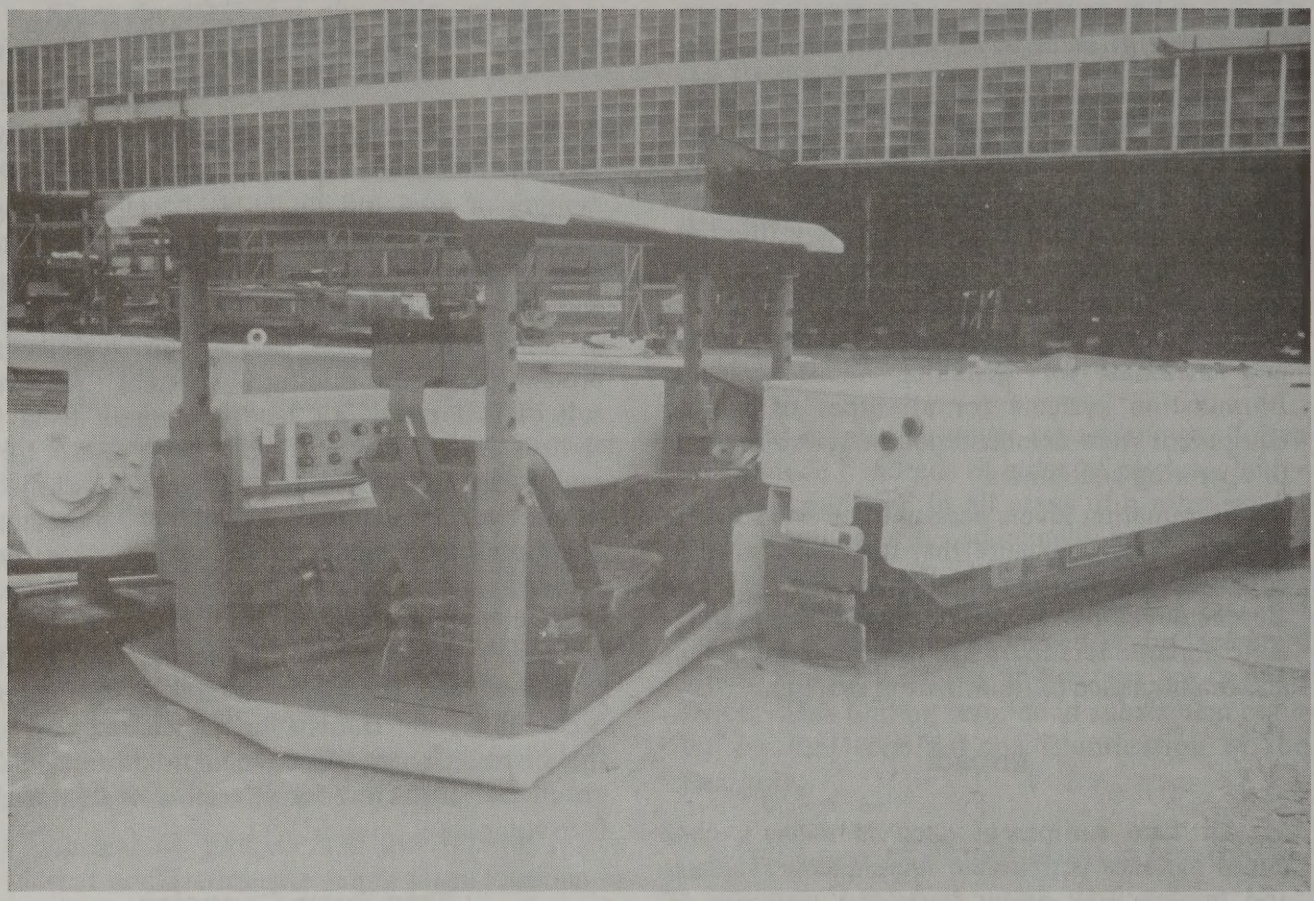


FIGURE 49. - Bureau-developed protective operator compartment on mobile bridge carrier.

cessful operator compartment design for thin-seam applications.

A second, innovative approach to the problem has been the Bureau's development of the technology to teleoperate mining systems. Teleoperation involves a direct approach to providing protection for thin-seam equipment operators—relocating them from the immediate hazard zone to a safe location. Teleoperation for mining can be described as the computer-based, remote control of mining machinery from a protected operator compartment located some distance from the minesite, so that sensory information about the mining operation cannot be obtained directly. Video, sound, and other relevant information is gathered through sensors and is transmitted electronically to the operator's location. The teleoperator responds to the information and makes decisions that are initiated by activating controls. These control commands are then electronically transmitted to the remote machinery, and the appropriate machine functions are carried out. Teleoperation also separates operators from health and congestion problems at the face area and substantially enhances their comfort.

Figure 50 shows the Bureau's teleoperation technology being used to control a new highwall mining system. Additionally, Bureau teleoperation technology is being utilized by a major highwall system manufacturer and several large mining companies that have developed their own highwall mining systems. Teleoperation of mining equipment is a state-of-the-art application of advanced electronic technologies to foster safety in thin seams. The technique has been successfully applied to highwall mining and appears promising for a deep, room-and-pillar mining system under development. Teleoperational systems should bridge the gap between current, hazardous methods of controlling thin-seam mining equipment and highly automated systems likely to evolve within the next 20 years.

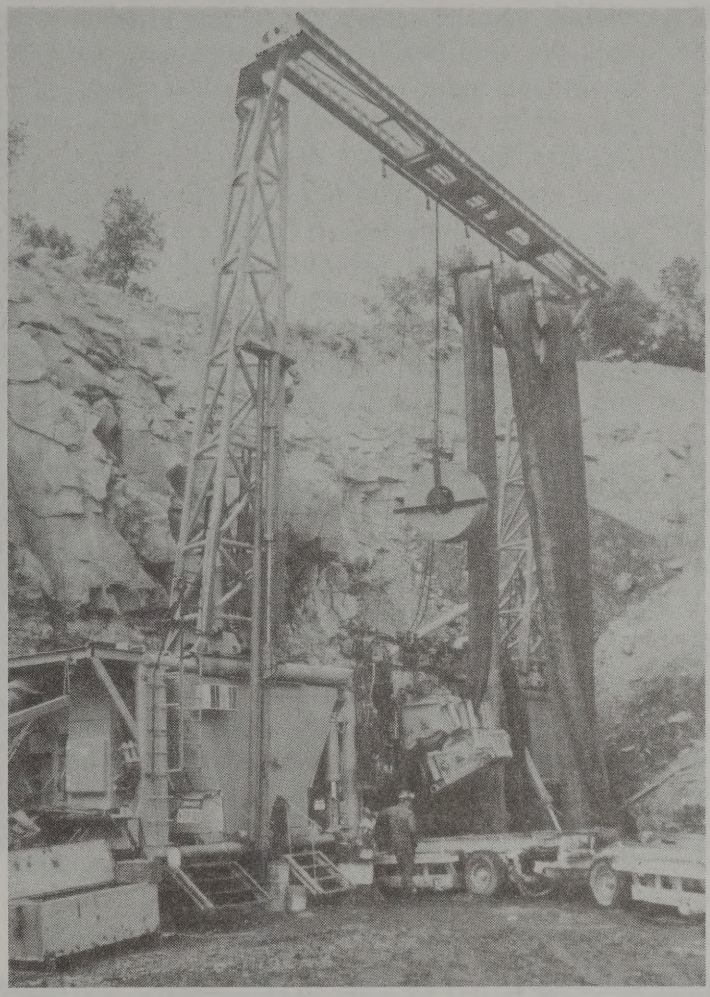


FIGURE 50. - A teleoperated highwall mining system at a test site in northern West Virginia. The teleoperator's protected station is to the left of the active entry.

OPERATOR COMPARTMENTS AND CANOPIES FOR UNDERGROUND FACE EQUIPMENT

The Bureau has sponsored several research projects on equipment operator canopies, compartments or cabs, and controls to improve protection for and better accommodate the needs of the operator. During the initial phase of current shuttle car research, investigations focused on limited or partial-coverage canopies to better protect the operator in thin-seam mines. Three different designs were produced, which included the roll-bar, sliding canopy, and flip-top configurations (fig. 51). These designs eliminated a major drawback of traditional cab and canopy designs—obstructed viewing for the operator—and protected the operator from the most frequent cause of shuttle car operator injuries, pinching and/or squeezing between the machine frame and the roof or rib. Building on the results of the preceding research, the Bureau continued efforts to produce an acceptable, fully protective operator cab for thin-seam shuttle cars. The resulting cab design will give the operator's needs chief priority compared with traditional design criteria and will reflect a suitable compromise among the features of operator safety and comfort, vehicle transport capacity, and maneuverability. Present work includes modifying a thin-seam shuttle car received under a Memorandum of Agreement with a cooperating coal mining company, fitting the car with the Bureau-developed ergonomic operator cab, and field testing the novel cab-shuttle car configuration in the selected mine (fig. 52).

MOBILE MINING EQUIPMENT SAFETY

Starting in the 1960's and continuing throughout the 1970's and 1980's, there has been a dramatic increase in the size, power, and speed of mobile mining equipment. As the equipment evolved, corresponding research was needed to insure the continued safety of the equipment operators. The Bureau addressed this need for safety innovations through many diverse equipment-related projects. Research concentrated on haulage trucks, front-end loaders, and conveyors, with many of the findings being applicable to other mobile equipment. The emphasis on equipment safety remains a major component of Bureau research.

Haulage Trucks

When large haulage trucks are used in deep open pit mining operations, they traverse long, downhill stretches of roadways. Occasionally, owing to mechanical failure or human error, the operators may lose control. In the early 1980's, work was performed on techniques that could be utilized to stop runaway trucks. It was found that edge-of-road berms would be inadequate. The primary techniques that would work were

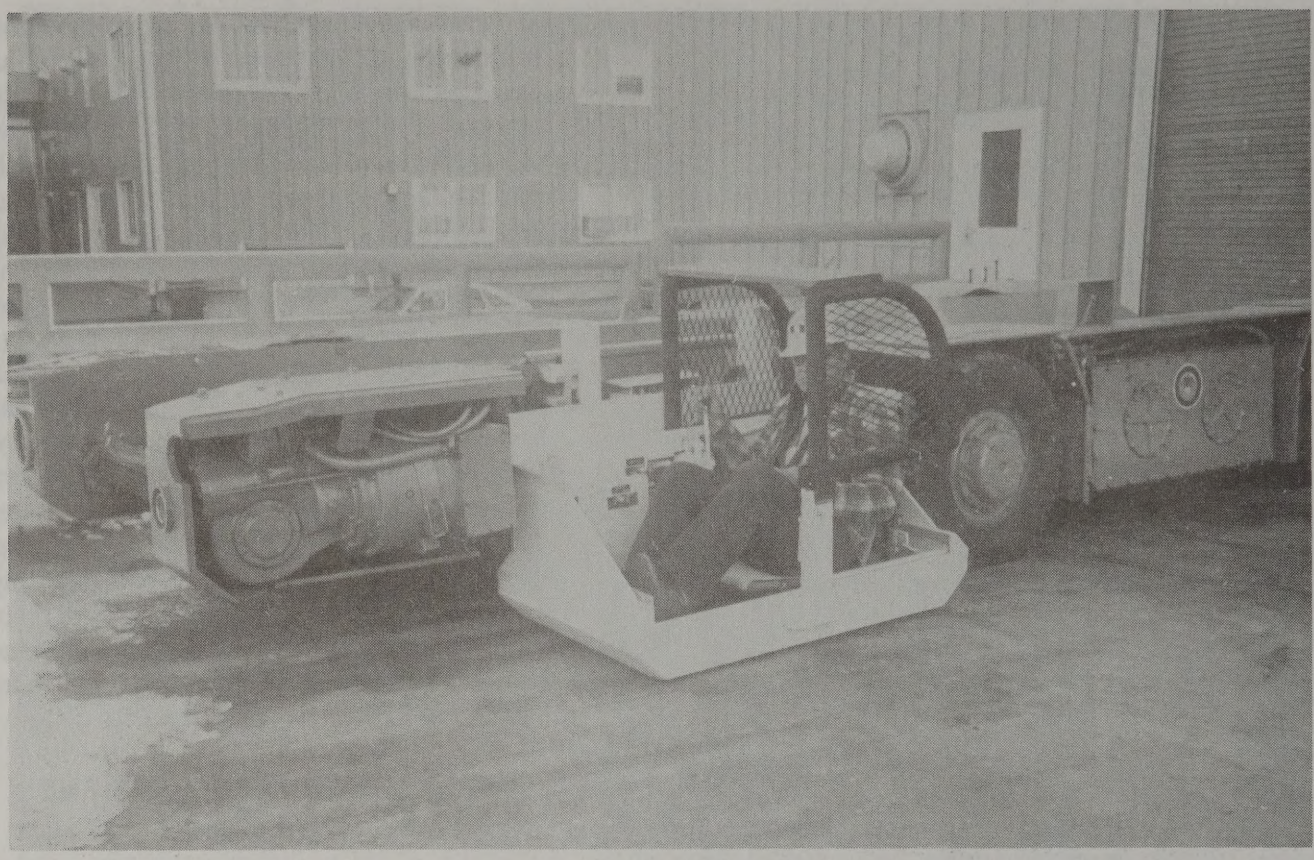


FIGURE 51. - Flip-top operator compartment.

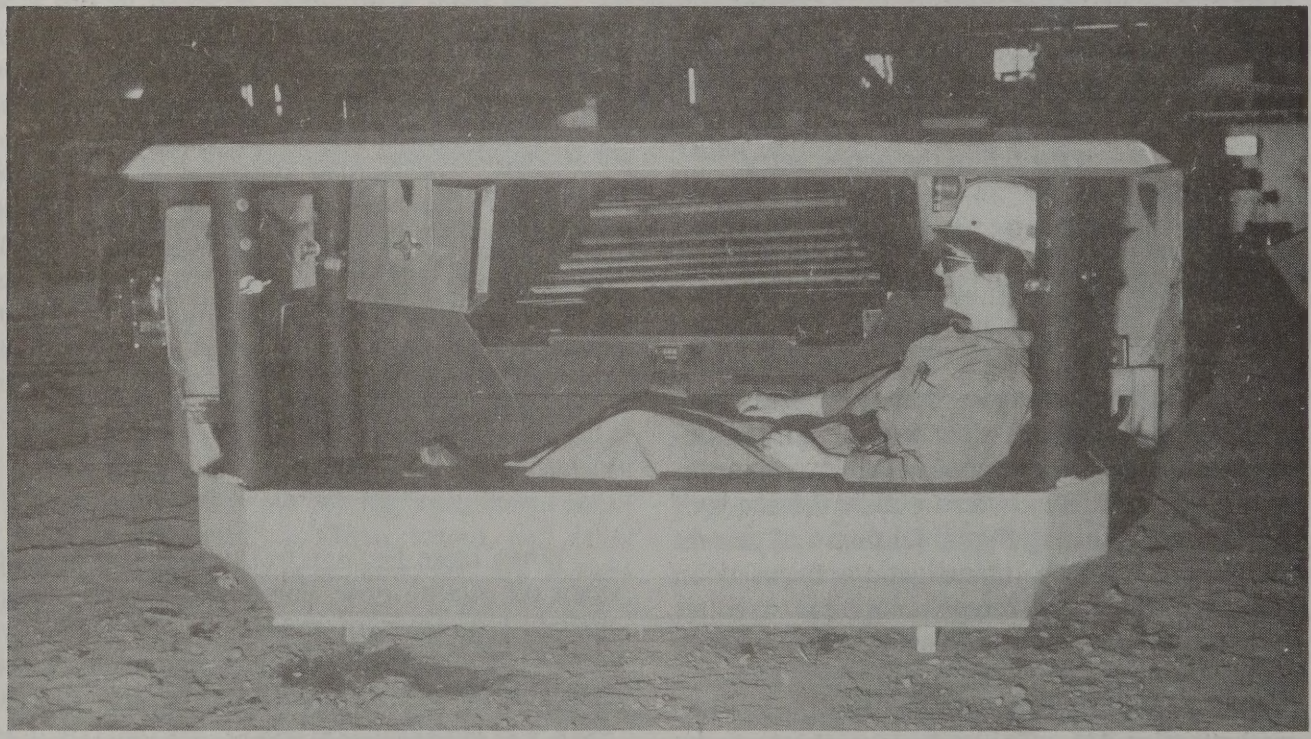


FIGURE 52. - Bureau-developed operator compartment designed for thin-seam shuttle cars.

escape lanes and safety center berms. Safety center berms were evaluated and found to provide many advantages to the mine operations over escape lanes. Recommendations on construction techniques and safety center berm design are available for mining operations as a result of this research.

As the size of haulage trucks increased, driver visibility became a major problem. Large blind areas were found to the rear, right side, and front of the trucks. This presented serious problems to small vehicles or pedestrians who were working around the trucks. Bureau research addressed this problem through the development of visibility aids and electronics-based collision avoidance technology.

The initial approach involved the development of new mirror designs that would provide a larger field of view to the operators. In particular, a rectangular, convex mirror with a large radius curve was developed for the right side of the truck. These mirrors, along with improved mirrors for the left side of the truck, are now commercially available. Recommendations on haulage truck mirrors that include optimum mounting locations were published.

Continued research resulted in the development of a collision avoidance system based on electronic transmitting techniques. A signal transmitter is mounted on the smaller vehicle to be detected. Continuous signals from this transmitter are sensed by receiving antennas mounted on the right, front, and rear of the haulage truck. Upon receiving a signal, a buzzer and/or warning light in the cab of the truck is energized, alerting the operator to a potential collision. During field trials, the systems performed well, actually preventing a possible accident. The mining industry has expressed a significant interest in this type of system, with many requests for system information and availability.

A significant number of accidents and injuries occur to operators as they mount or dismount from the truck. To alleviate this problem, crash-resistant steps were developed and tested that would extend closer to the ground and flex upon impact. The steps were designed to provide secure and firm footing, not flexing under the weight of the operator. The experimentation performed under this project provided the concepts and fundamental design premises currently being used by many equipment manufacturers. Bureau research also provided assistance in the development of a powered safety step. This unit provides access to large-tracked vehicles such as dozers, shovels, etc. Powered safety steps are currently being manufactured.

The Bureau currently has a project oriented to the reduction of dump point accidents (fig. 53). These accidents primarily involve the fall of haulage trucks over the crest of stockpiles and waste dumps. A slope stability program was developed that provides safe operating distances from the slope edge. The distances are based upon material strength parameters, vehicle dimensions, vehicle speed, and braking distance while backing to the slope edge. The software and accompanying user's manual are being prepared for industry use. Final work in this area involves the development of informational aids to assist in the training of equipment operators regarding stockpile hazards.

Current research also involves the measurement and characterization of shock and vibration levels on mobile mining equipment. The information will eventually provide specifications for the manufacture of ruggedized equipment components. The data collected are also assisting in the development of novel seat designs. Seat designs currently being studied may provide improved isolation from shock and vibration loadings, which are responsible for a significant number of operator injuries.

Loaders

Front-end loaders are similar to haulage trucks in that they have a large blind area behind the machine. Bureau research was instrumental in the design and development of a discriminating backup alarm currently being widely marketed. The discriminating backup alarm differs from standard backup alarms in that it sounds only when a person or object is in the blind area. This provides several distinct advantages. A standard backup alarm is continuously activated, so that the alarm becomes a normal part of the mine environment and less effective as a warning device. Additionally, when several machines are operating in close proximity, it is difficult to detect by ear alone exactly which machine's backup

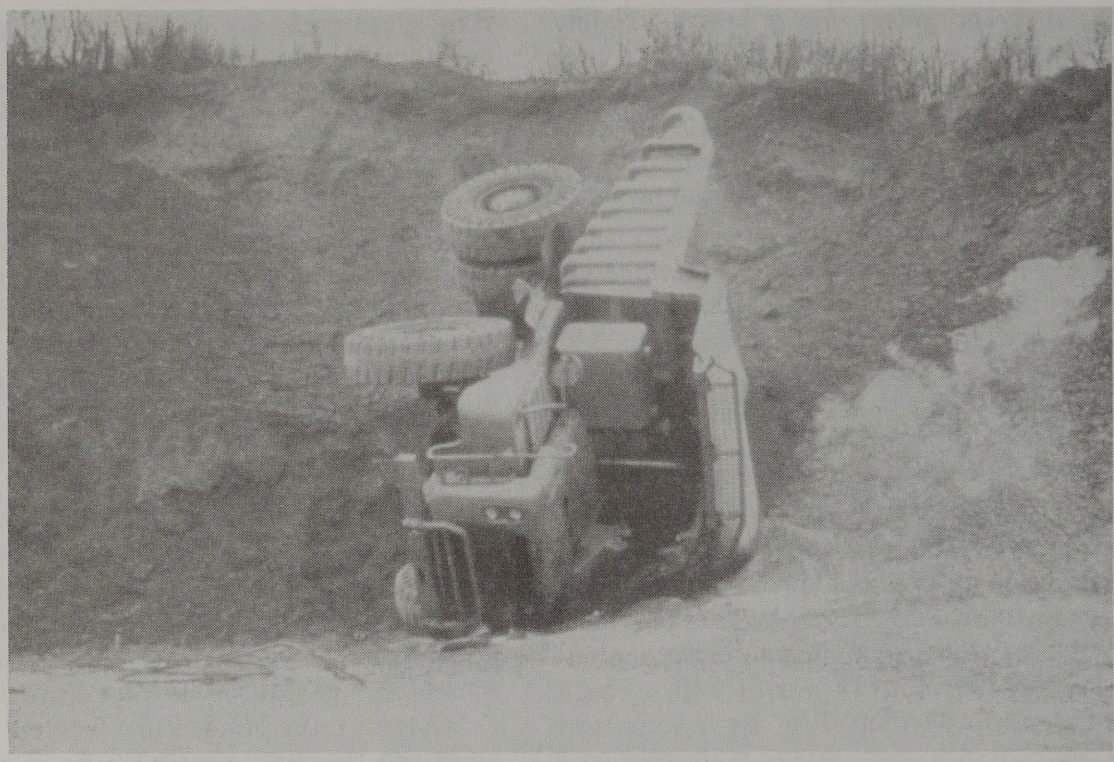


FIGURE 53. - Dump point accident.

alarm is sounding. Discriminating alarm technology eliminates both of these problems.

To assist maintenance personnel, MSHA inspectors, and equipment manufacturers, a guide was developed for the inspection of rollover protective structures (ROPS). The manual describes the types of defects to look for and includes a checklist for performing inspections. ROPS research also involved performance rollover tests on large front-end loaders. The research consisted of rolling over 268,000- and 390,000-pound front-end loaders. The loaders were instrumented to determine the accelerations, loads, and deflections placed on the ROPS. As a result of these tests, recommendations were made for the modifications of existing standards for front-end loaders greater than 240,000 pounds. This research also involved development of a vest restraint system. The vest restraint was tested on instrumented crash dummies during the rollover tests and performed well.

Conveyors

Numerous accidents occur to personnel cleaning up carryback from under conveyors. In fact, shoveling and cleaning around moving conveyors is the most hazardous activity associated with conveyor systems. The Bureau initiated a study of the parameters affecting the operation of conveyor belt cleaners, with the goal of reducing carryback. As a result of these efforts, fundamental properties about blade wear and carryback were discovered. These findings resulted in the development of a pneumatic blade, which eliminates irregular blade wear and nearly eliminates carryback.

Future Directions

The Bureau will continue to emphasize mobile mining equipment safety in its research program. As mining methods evolve and equipment technologies change, the impact upon workers' safety will need to be continually monitored. The development of new safety technol-

ogies that can assist industry in maintaining the highest mobile equipment safety standards will continue to be the overriding research goal.

HOISTING SYSTEMS DEVELOPMENT

The Bureau of Mines has been involved in research on hoisting systems for more than 20 years. There are about 450 mine shafts and slopes in the United States. Because many of the personnel cages in these mines are suspended from a single wire rope, there is a significant safety concern with regard to the condition of ropes during their lifetime. The major contributions to the degradation of a wire rope are fatigue due to bending over the head sheave and corrosion resulting from operation in a hostile environment.

To obtain quantitative data on this deterioration, a Wire Rope Research Laboratory was built by the Bureau in the early 1980's (fig. 54). In December 1984, a tensile test machine became operational that had the capability to break wire ropes at up to 800,000 pounds and to perform axial fatigue tests. Thus far, about 500 samples have been evaluated on this machine.

In January 1987, an innovative bending fatigue machine began operation. Its unique capability is to generate nine different fatigue levels on a single, 1,000-foot-long section of wire rope at speeds up to 1,000 feet per minute and tensions up to 300,000 pounds. While a rope is being cycled, electromagnetic nondestructive testers (EM NDT's) monitor its condition. Upon reaching a selected level of fatigue, samples are cut for destructive testing on the tensile machine and for metallographic examination. To date, data have been compiled on four 2-inch-diameter and three 1-¼-inch steel wire ropes, as well as one 1-⅞-inch-diameter synthetic fiber rope (fig. 55). The synthetic fiber rope is of especial interest to the mining industry and MSHA because it does not corrode and has a high strength-to-weight ratio. Data analysis on these tests is in progress. To supplement the laboratory data, five Memorandums of Agreement have been executed with mining companies to provide field rope samples for tensile testing.

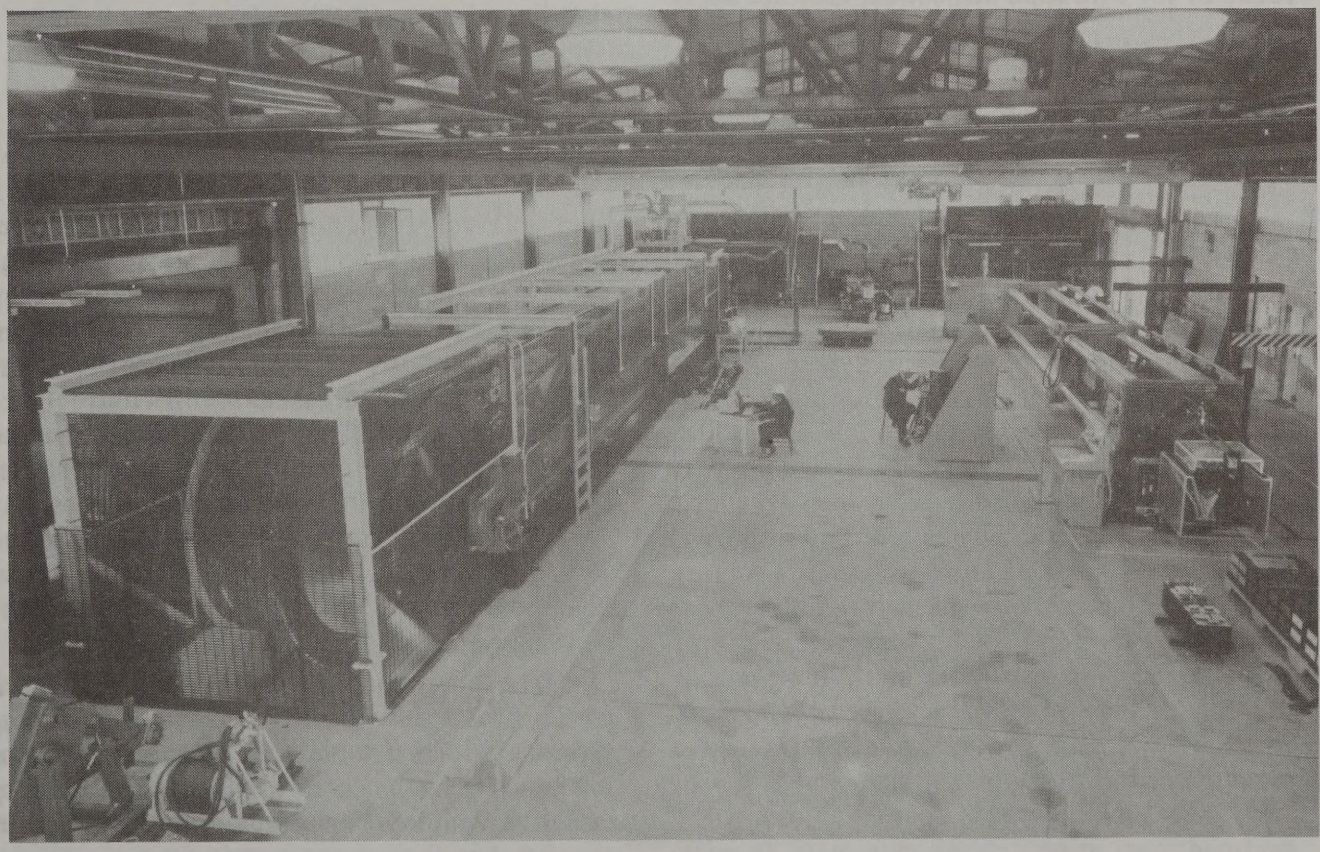


FIGURE 54. - Research to improve safety and economy in the hoisting of personnel and materials in underground mines is conducted in the Bureau's Wire Rope Research Laboratory.

FIGURE 55. - Bending fatigue test on 1 7/8-inch synthetic rope.

The general corrosive behavior of wire rope has been evaluated in the laboratory, where field ropes have been studied to reveal the effectiveness of field-applied lubricants and mine maintenance procedures. An extensive amount of evaluation has been done on the capability of EM NDT's to determine the condition of laboratory and field wire ropes. While not officially required for wire rope inspection, they are fairly widely used in the mining industry. Research has redefined the role of such devices in wire rope inspection, led to several improvements in the performance of commercial units, and provided significant input in the generation of a new American Society for Testing and Materials standard for acceptable performance.

Metallographic studies of wire ropes are also conducted by the Bureau. This work is very complex, since the changes in the structure of the steel during the process of fatiguing are subtle.

Lastly, the Bureau works closely with MSHA and the Canadian government through a cooperative agreement for maximum exchange of information on hoisting regulations and working experience.

The long-range goals for these projects are to generate sufficient data for MSHA to improve the regulations for greater safety and better efficiency of hoisting operations. It is believed that this work can ultimately eliminate the danger of accidents in the hoisting of personnel and materials in underground mines.

DISASTER PREVENTION

METHANE CONTROL

Coal Mines

The explosion or ignition of methane has been a major cause of multiple fatalities in underground coal mines in the United States. In the early 1900's, as many as 500 miners per year were killed in coal mine explosions. This high fatality rate was gradually reduced by improved ventilation practices, removal of ignition sources from the mine, the use of permissible explosives, the development of "explosion-proof" electrical equipment, stricter and more accurate tests for methane, and the control of coal dust, which often combined with methane to create a particularly hazardous condition. Even though the fatality and injury rate due to explosions has declined, coal mine explosions remain an ever-present danger. The mining of increasingly deeper and gassier coalbeds reflects a particularly ominous trend. In 1989, U.S. coal mines were producing approximately 304 million cubic feet of gas per day, an increase of approximately 19% since 1980 and a 41% increase since 1975. While mine methane emissions have increased significantly since implementation of the 1969 Act, fatalities and injuries resulting from explosions have remained relatively low (averaging fewer than seven fatalities per year between 1978 and 1987), owing in part to the fundamental coalbed methane research conducted by the Bureau.

The coal mine methane control research program was developed to provide the mining industry with the tools necessary to assess the methane hazard prior to mining and to develop effective ventilation and gas drainage practices to control or capture gas entering the mine atmosphere. Fundamental research on coalbed gas was conducted to determine the factors that con-

trolled the storage and migration of gas in coal. Bureau research has documented that within a coal basin the gas content of individual coalbeds generally increases with increasing rank and depth. Regional or basinwide assessments of the volume of in-place gas were conducted for several of the gassiest coalbeds in the United States, including the Pittsburgh, Mary Lee/Blue Creek, Beckley, Hartshorne, Freeport, and Kittanning Coalbeds. The development of the direct method test for gas content testing of coal samples provided mining companies with the ability to determine the relative gassiness of their coal reserves during exploratory drilling prior to mine development (fig. 56). With the regional and site-specific methane assessment techniques, a company could, as part of the initial mine design, better plan ventilation needs and determine the potential need for auxiliary methane drainage. These Bureau-developed assessment methods have been widely adopted by the coal industry and are routinely practiced by the major coal companies and by consultants and service companies to the mining industry.

The primary means of controlling mine methane emissions is ventilation. The coal mine ventilation research program has concentrated on fundamental research to evaluate the effectiveness of mine ventilation and cost-effective ways of maximizing the efficiency of all the mining activities and practices that influence a mine's ventilation system. The pioneering use of tracer gases for in-mine ventilation assessments was a significant factor in determining where and how methane enters and disperses in the mine atmosphere, leading to the development of improved ventilation technology. Ventilation technology improvements have primarily focused on controlling face emissions at the mining machine and upgrading general minewide ventilation practices. Machine-mounted water sprayfans and scrubbers have been developed for maximizing ventilation efficiency on both continuous miners and longwall shearers. Basic research on the sequence of coal cutting with longwall shearers indicated that gas levels at the face could be reduced by reverse drum rotation.

Research on stoppings has led to the development of construction and coating recommendations to minimize the volume of air leakage, thereby effectively increasing the volume of ventilation air for methane dilution without actually increasing the volume of air entering the mine.

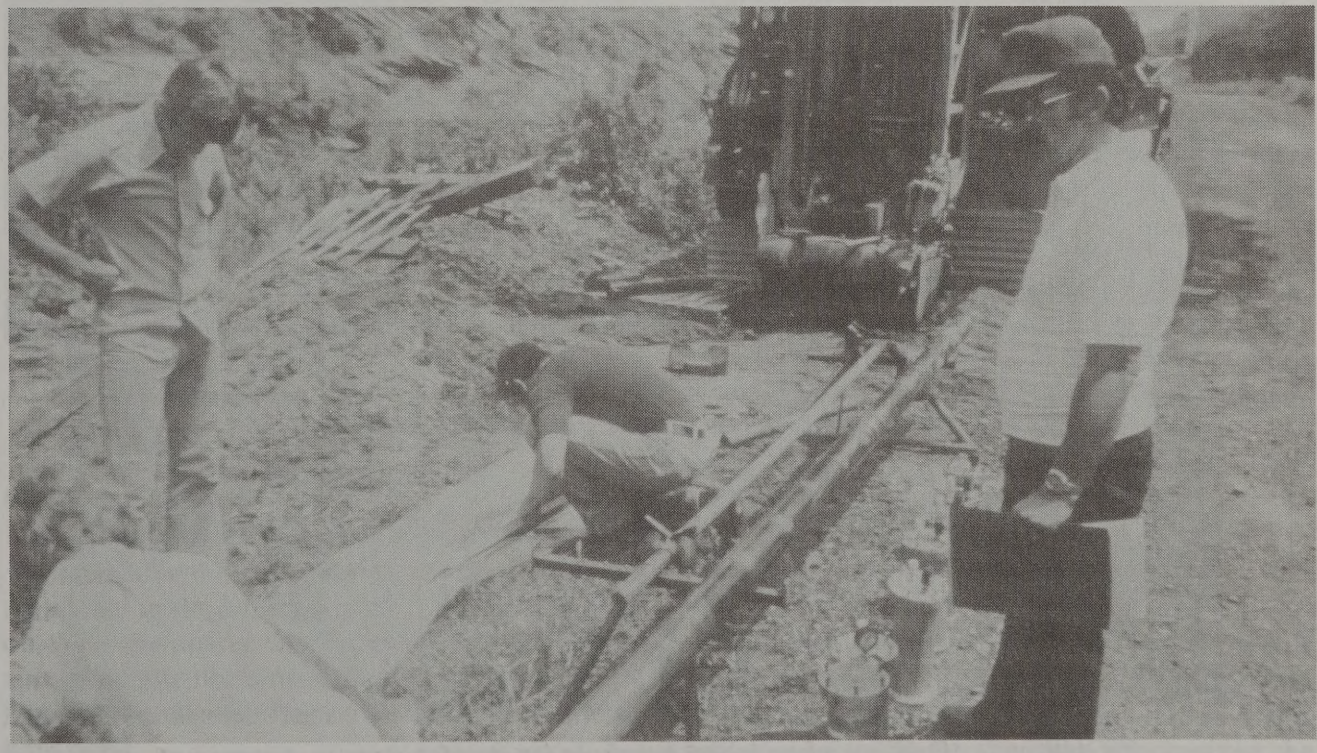


FIGURE 56. - Bureau engineers collecting coal samples for direct method gas content determination.

When ventilation alone cannot effectively control underground methane emissions, methane drainage may be necessary to maintain safe working conditions at optimum coal production rates. The Bureau has developed several methane drainage techniques that can be used during or in advance of mining to provide the mining company with the appropriate solution to site-specific geologic and engineering conditions. In existing mines where a short-term immediate solution is required, horizontal holes drilled into the unmined coal have been shown to provide significant relief (fig. 57). This technique is the most widely used gas drainage method in the United States for methane drainage on longwall panels. Vertical gob gas ventholes or cross-measure holes drilled into the strata above the panel are also an effective, immediate, short-term solution (fig. 58). If sufficient lead time is available, longer-term gas drainage techniques such as stimulated vertical boreholes, horizontal boreholes from shaft bottoms, or directionally drilled holes from the surface can be included as part of a comprehensive mine design. In an evaluation of the effectiveness of a long-term vertical borehole gas drainage system in the Mary Lee Coalbed in Alabama, it was found that after 10 years of gas production approximately 75% of the gas in place had been removed from the coalbed (fig. 59). This represented more than 3.2 billion cubic feet of gas that will never be encountered underground by the mining operation. The use of auxiliary methane drainage systems has permitted the safe and efficient mining of coal in situations where mining would otherwise not be possible.

Metal and Nonmetal Mines

The study of methane occurrence in metal and nonmetal mines is a relatively recent Bureau research effort. While methane is formed from coal during the thermal maturation process, its origins in some metal and nonmetal mines are still poorly understood. Although the amount of methane released in metal and nonmetal mines is generally smaller than the volume of gas from coal, the results are no less costly and dramatic. The Bureau research program was initiated following an ignition of methane in a Louisiana domal rock salt mine, resulting in five fatali-

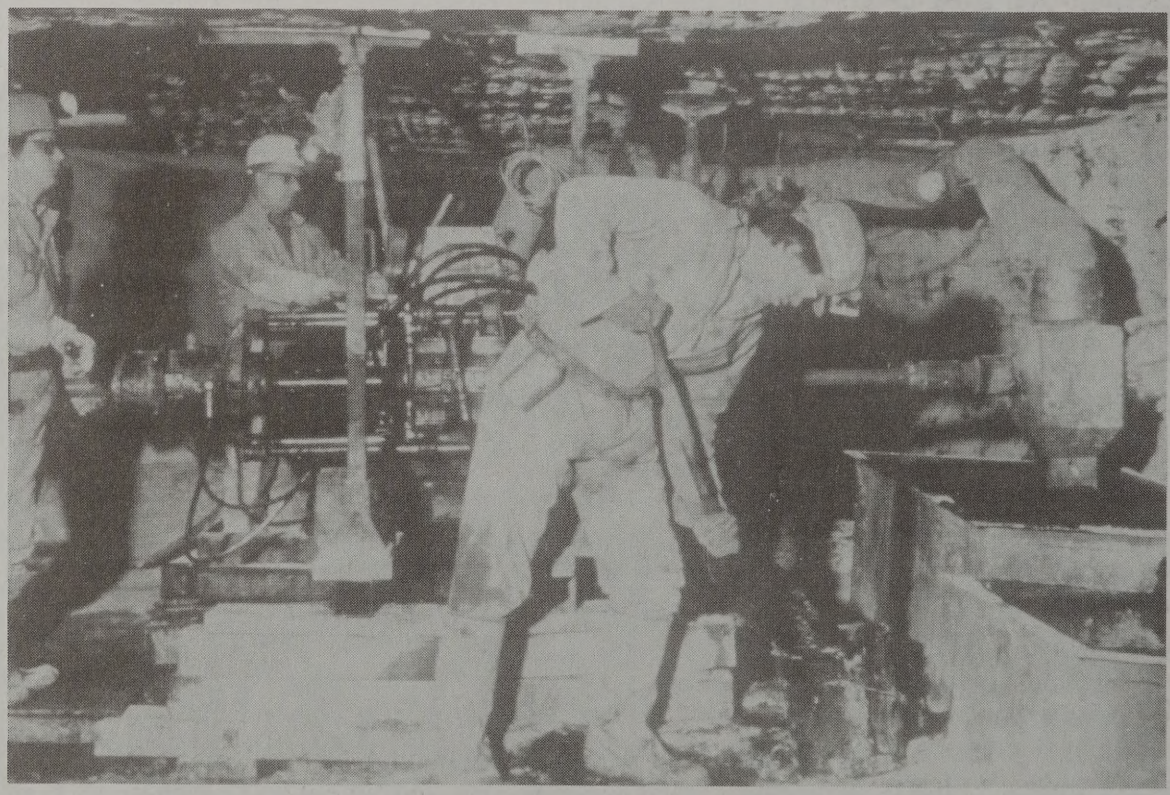


FIGURE 57. - Drilling a horizontal borehole for gas drainage in advance of or during mining.

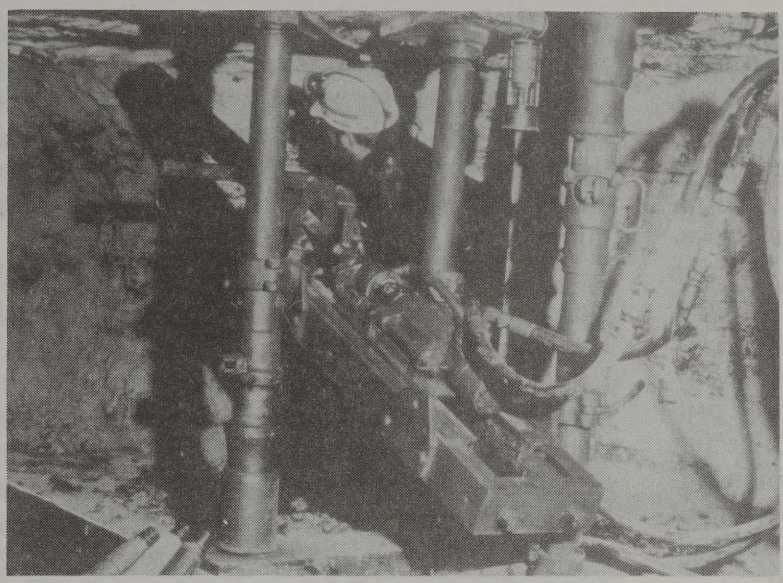


FIGURE 58. - Drilling a cross-measure borehole for gob gas drainage.

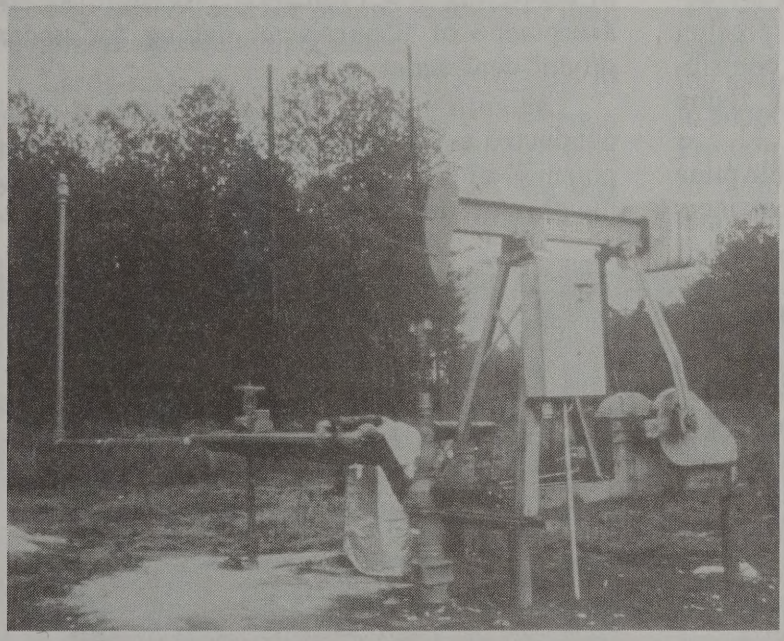


FIGURE 59. - Surface production facility in Alabama for stimulated vertical boreholes.

ties. Methane ignitions have continued to take lives in metal and nonmetal mines.

To reduce the danger of methane ignitions in metal and nonmetal mines, research has focused on the development of a methodology to measure methane emissions and basic studies to enhance the understanding of methane storage and emissions.

For measuring the amount of in-place gas, the dissolution method was designed for determining the methane contents of domal salt samples or other evaporite rock samples. A more expedient method of measuring the gas from domal rock salt samples, the acoustic method, was designed to perform less as a research tool and more as a detection system for mining companies. This method allows the companies to test all working faces at the start of each shift. Additionally, a highly accurate test—the modified direct method—was developed to measure methane emitted from Green River oil shale and other organic rocks. These data were required for both industry and regulatory agencies for input on how oil shale mines should be designed and operated to maintain safe conditions underground.

Once methane emissions/contents have been established, they can be related to potential geologic controls. In all metal and nonmetal mines, increased methane contents have corresponded to increased methane emissions. To describe or characterize rock exposures or samples, mine areas can be mapped and hand samples can be described. Samples can also be characterized petrographically to identify features distinguishing high-gas from low-gas samples. Other tests can be performed to characterize the methane emission potential, including permeability studies, total organic carbon, thermal maturation, x-ray diffraction for mineral composition, and sorption isotherms.

FIRES AND EXPLOSIONS

Fire Research

Control of mine fires is one of the Bureau's most important objectives. The underground fire at Sunshine Mine, Kellogg, ID, in 1972, which resulted in 91 fatalities, emphasized the need for research to better control combustible

materials introduced into underground mines, to improve fire warning systems, to develop more efficient methods for mapping safe escapeways, and to develop more effective methods for fighting underground fires. A concerted effort to meet these needs was initiated in 1973. This required the development of improved test procedures for evaluating the fire resistance of mine combustibles, new fire detection technology, mathematical modeling techniques to predict the spread of heat and toxic products from underground fires, new mine sealing and inerting procedures, and a better understanding of mine fire phenomena. Another problem was the high frequency of equipment fires, which underscored the need for automatic fire suppression systems for both mobile and stationary equipment.

Fire Prevention and Suppression.—Fundamental studies of methane flame suppression were conducted to deduce how chemical inhibitors work. The results were utilized in the development of mine fire and explosion suppression systems and significantly contributed to a broader understanding of flame chemistry.

The fire hazards of storing combustible mine fluids in 5-gallon plastic and steel containers were investigated, and a test procedure was developed to assess the failure modes of partially filled containers subjected to a fire. The results were used by MSHA to support Federal regulations and to develop policy statements on the storage of flammable fluids in underground mines.

The flammability of rigid plastic mine ventilation tubing was evaluated by in-mine fire trials and large-scale vertical fire trials at the Bureau's Lake Lynn Laboratory. The results significantly contributed to the adoption of a new Federal standard test procedure for fire-resistant ventilation tubing. The flammability of mine conveyor belting was also assessed in large-scale fire experiments (fig. 60), the results of which clearly demonstrated the inadequacy of the current Federal acceptance test for fire-resistant belting. A new laboratory-scale fire test procedure for belting was developed and evaluated. MSHA plans to adopt this new evaluation procedure for the acceptance of fire-resistant belting for underground coal mines.

Laboratory- and large-scale studies were conducted to determine the spontaneous heating potential of coals and sulfide minerals, to define the physical and chemical factors that contribute

FIGURE 60. - Large-scale flammability test of conveyor belting in the surface fire gallery at Lake Lynn Laboratory.

to the self-heating process, and to evaluate the effectiveness of additives and sealants to suppress spontaneous combustion (fig. 61). Results have been used by MSHA and the mining industry to reduce the risk of spontaneous combustion fires.

The fire endurance of concrete block and steel stoppings was investigated in full-scale in-mine trials. The results showed that both the block and steel stoppings retained their structural integrity and prevented the passage of smoke and fire gases. The study findings contributed to an MSHA policy statement permitting the use of steel stoppings in underground coal mines.

An investigation of the ignition temperatures of coal and oil shale dust layers on hot surfaces was conducted. Minimum hot surface temperatures at which dust layers of various thicknesses ignited were measured. The results were utilized by MSHA and the mining industry to limit equipment surface temperatures.

Large-scale studies on the extinguishment of oil shale rubble fires were conducted, wherein 85-ton piles of oil shale rubble were ignited with burning liquid fuels and a deep-seated fire was permitted to develop. Water was found to be more effective than foams for extinguishing the fires. A model for estimating the minimum amounts of water for quenching a rubble pile fire was developed, as well as a strategy for fighting oil shale fires.

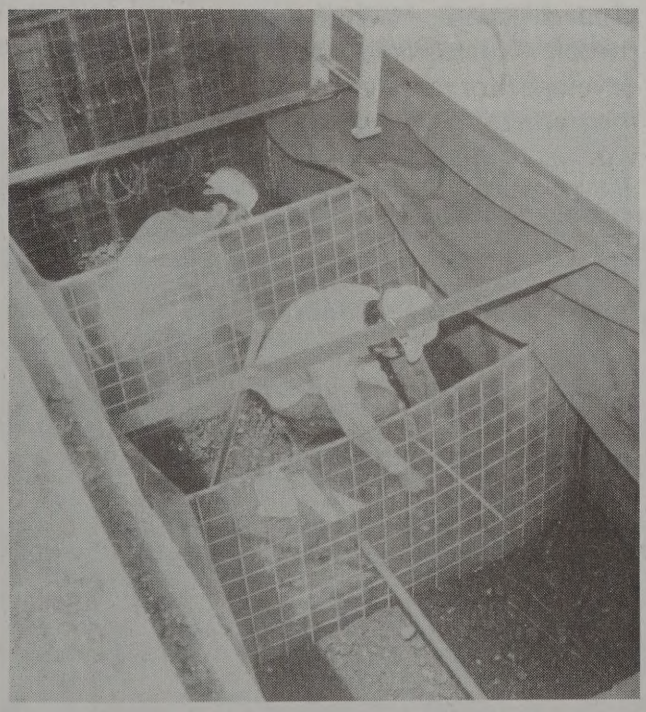


FIGURE 61. - Inserting temperature probes into a 15-ton coalbed to study the self-heating hazards of coal.

An automatic fire suppression system was developed to detect and extinguish large surface mining truck fires before they threatened the operator or caused severe equipment damage. When a fire was detected, dry chemical extinguishant was automatically discharged into the engine compartment. A wide variety of spinoff systems were developed and tested that satisfied the special requirements of other equipment types. The result was the commercial availability of cost-effective hardware systems that met the fire protection needs of the surface mining industry.

Underground mine fire suppression research was conducted to address diesel fire protection issues. Multipurpose dry chemical extinguishing systems were found to be the most effective in suppressing typical fires on diesel equipment. Prototype systems were developed that provided for automatic actuation of the suppression systems and included options such as automatic fuel supply shutoff and automatic brake application. Numerous prototype system configurations were evaluated, followed by laboratory tests of system components and long-term field trials of complete systems. Comprehensive fueling system design criteria were developed to reduce the chances of a spill or ignition at any stage of the fuel handling process. Additionally, various fire suppression system designs were developed for the fuel storage area and vehicle refueling area.

The performance of belt conveyor fire suppression systems in actual fire situations has not always been favorable. Analysis indicated that, although systems had been installed in accordance with the regulations, they were not functioning properly during fires. Standard reliability analysis techniques were applied to belt conveyor systems, and improved inspection and maintenance procedures were recommended.

Expanding upon technology that had been developed to locate and communicate with miners trapped underground by a mine disaster, a novel alternative to existing fire warning methods was developed. The new system utilizes

ultra-low-frequency radio waves to transmit a signal through the earth from a surface transmitter to small, person-wearable receivers underground. Tests of prototype equipment have achieved transmission distances of more than 5,400 feet.

Following are additional accomplishments:

- Fire-resistant hydraulic fluids based on water-oil emulsion were developed for underground mining equipment.

- Various types of fire suppression systems for conveyor belt drive areas in underground mines were evaluated.

- An investigation into the effect of timber size and spacing on the propagation of large-scale timber fires led to the establishment of guidelines for timbering in noncoal mines.

- A large-volume inert gas generator for combating deep-seated mine fires was successfully demonstrated.

- The fire hazards of self-contained self-rescuers (SCSR's) were evaluated, proving that their safety advantages outweigh any potential disadvantage. This work was instrumental in authorizing the introduction of SCSR's in underground coal mines.

Mine Fire Detection and Fire Diagnostics.—Numerous fire detection and mine monitoring systems were designed, fabricated, and subjected to long-term in-mine evaluations (fig. 62). A number of these evaluations included actual in-mine fire testing. Systems typically incorporated smoke and carbon monoxide gas detectors. Various instrumentation and computer-controlled monitoring systems were shown to exhibit the desired sensitivity and long-term stability and reliability. The result of this research is a wealth of commercially available mine fire detection systems.

A novel submicrometer particle detector was developed for use as an early warning fire sensor in underground coal mines. The sensor was also found to have potential as a continuous monitor of diesel particulate levels.

Fire detectors were also developed that can discriminate between combustion products generated by a fire and those generated from diesel engines. Such detectors are needed in mines that use diesel-powered equipment in order to eliminate nuisance alarms.

Prototype optical devices were developed that can measure average methane levels in a face area remotely without the need for personnel to travel under temporarily supported roof to make required 20-minute gas measurements. Such devices were also found to provide early and rapid detection of methane in the ventilation airflows or layered near the roof when mounted on moving mine vehicles.

Studies of the yields of combustion products from typical mine combustibles provided data that were used to assess the detectability of fires with product-of-combustion fire sensors. These data, along with additional data on the growth of fires, were used to develop guidelines for spacing of mine fire sensors in underground coal mines. They were also used to assess the severity of the toxicity associated with combustion product gases. Correlations between smoke particle characteristics and relative toxicity were developed for rapidly assessing the potential of a mine combustible to produce a toxic atmosphere when burned.

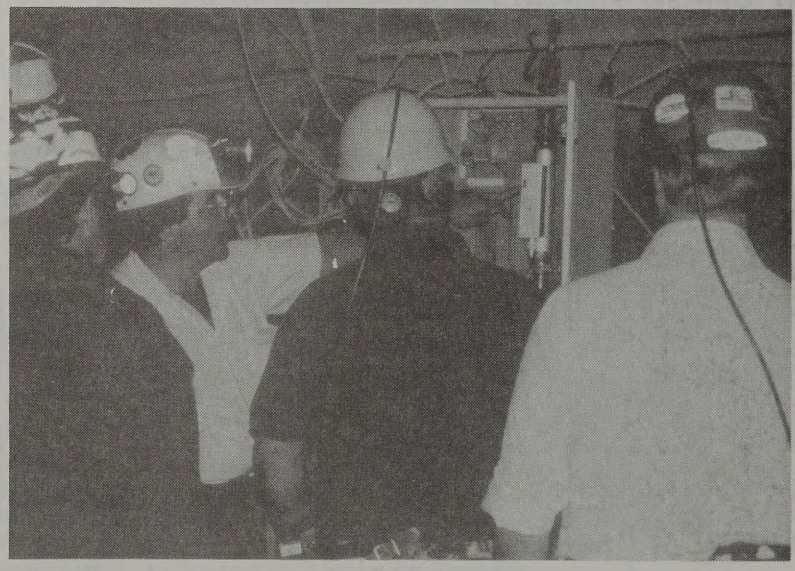


FIGURE 62. - A Bureau researcher demonstrates a fire detection system at Lake Lynn Laboratory.

A new gas ratio technique was developed that more reliably predicts the potential for safe recovery of mines sealed due to fire. This ratio also has potential for the early detection of spontaneous heatings in gob areas.

The effects of fires on mine ventilation airflow were studied, and subsequent expressions were derived to predict the potential of a fire to "throttle" the airflow. Diagnostic techniques utilizing carbon monoxide and carbon dioxide measurements were found to be useful in providing real-time information on the fire intensity and its effect on ventilation.

Experiments were conducted to define the minimum fire intensities for flame propagation as a function of air velocity. Subsequently, theoretical models were developed that reliably predict these fire levels. Flame spread models were developed and applied to experimental data on flame spread along conveyor belts, with favorable results.

MFIRE, a mine fire simulation computer program, was developed to enable modeling of mine fires (fig. 63). Using the program, mine personnel can predict the time-dependent distribution of combustion products throughout a mine network, thereby aiding the design and layout of fire detection systems, designation of evacuation routes, and development of firefighting strategies. MFIRE identifies recirculation paths and can predict where the thermal forces from a fire will cause ventilation reversals. The program can also be used for routine ventilation calculations and planning.

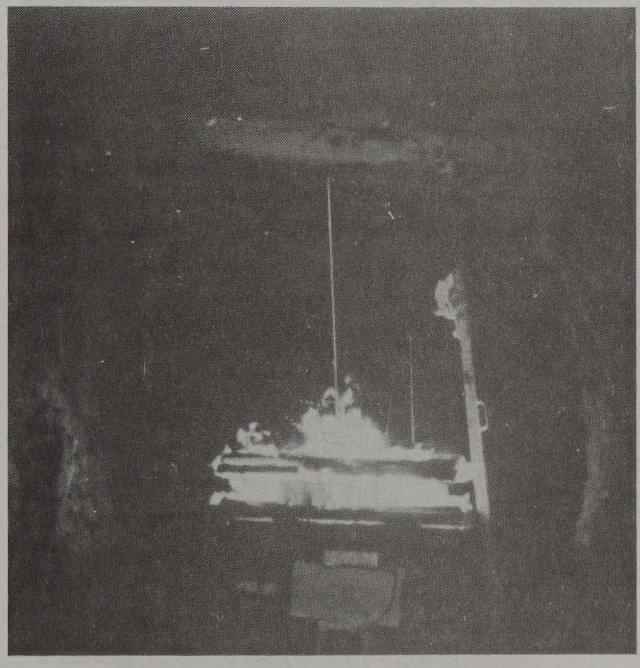


FIGURE 63. - MFIRE validation test at Waldo Mine, New Mexico.

Explosion Research

Control of mine explosions constitutes one of the Bureau's first research objectives, for it was the grave concern over a series of mine explosions in the early 1900's that led to the formation of the Bureau of Mines in 1910. In subsequent years, the Bureau's research and development made it an international authority in the realm of mine explosions. The rapid growth of mechanized mining in U.S. coal mines in the early 1970's created new explosion problems and exacerbated old ones, primarily because of the fineness and large quantities of coal dust produced. The change in production methods also eliminated any margin of safety associated with the practice of generalized rock dusting, developed when conventional mining was the rule rather than the exception.

Several techniques to supplement the dust explosion protection afforded by rock dusting had been identified. The most promising included active and passive systems to be mounted on equipment or installed in mine entries to quench or suppress methane ignitions or developing coal dust explosions. However, before any serious progress could be made in applying these concepts in U.S. coal mines, a groundwork of fundamental information on gas and dust explosion ignition, propagation, and extinguishment was needed. This included designing passive explosion barriers activated by the pressure wave ahead of the flame front in an advancing coal dust explosion, and triggered barriers for use on mining equipment, as well as supporting research on flame detection, the dispersion of gaseous and powdered inhibitors, and the development of diagnostic instrumentation.

Inerting Requirements for Mining.—For homogeneous dust deposits, comparison of single-entry tests showed that a greater amount of inert content is needed for wider entries to prevent flame propagation. Flammability tests have been conducted using gilsonite dust having a volatile matter content of 84%. For the rock dust inerting tests, the gilsonite required about

7% more rock dust than the coal dust to be inerted. These results for the gilsonite dust extend the data base for carbonaceous fuels to include a wide range of volatilities.

In Situ Assessment of the Mine Dust Hazard.—Evaluation of gamma and beta ray devices for determining rock dust content showed them to be inappropriate for general use underground in U.S. coal mines. Safety considerations negated their use in the harsh mining environment. The gamma ray units required massive samples weighing several pounds. The Bureau-developed optical meter for measuring rock dust content has been one of the most significant accomplishments. The optical reflectivity technique in conjunction with sample drying with molecular sieve spheres overcame all of the shortcomings of the devices utilizing strong radioactive sources. This rock dust meter is now undergoing commercialization and has great potential for improving explosion protection in mining operations and reducing excessive rock dusting.

Characterizing the Float Dust Hazard.—The Bureau has developed a float dust accumulation meter for rapidly detecting and controlling hazardous float dust accumulations. This device controls inert dusting on an as-needed basis and will provide to the mining industry a powerful tool for dealing with hazardous accumulations of float coal dust.

Large-scale float coal dust explosion studies conducted in the Bureau's Experimental Mine at Bruceton, PA, have shown that the top 4 millimeters of floor dust plays a major role in the early development of a dust explosion. Large-scale explosion tests have shown that a surface accumulation of about 0.1 millimeters in thickness, once entrained, can sustain flame propagation for several hundred feet. Research has shown that a surface accumulation of float coal dust of 0.08 millimeters in thickness on top of a previously rock-dusted base that has 80% total incombustible content will, once entrained, sustain a propagation. This underscores the seriousness of the float dust hazard associated with stratified layers.

Ignition and Explosion Processes.—Explosibility properties of coal dusts and hybrid mixtures of coal dust with methane and with inerting dusts have been reliably measured. The development of the Bureau's 20-liter explosibility chamber (fig. 64) constitutes an improvement over the smaller 8-liter chamber, giving better agreement with data from larger-scale explosions with particular igniter strengths. This explosibility chamber greatly aids as a screening tool in the planning of full-scale mine explosion tests by minimizing the number of tests of dry pure dusts and homogeneous mixtures of dusts. The explosibility chamber has been automated through the use of a computer. Various industries (e.g., chemical processing, metallurgical, grain) now have a reliable tool, developed by Bureau explosibility research, to rapidly and economically characterize the explosibility of dry homogeneous dusts.

The 1.2-liter ceramic furnace has yielded valuable data for the thermal autoignition tem-

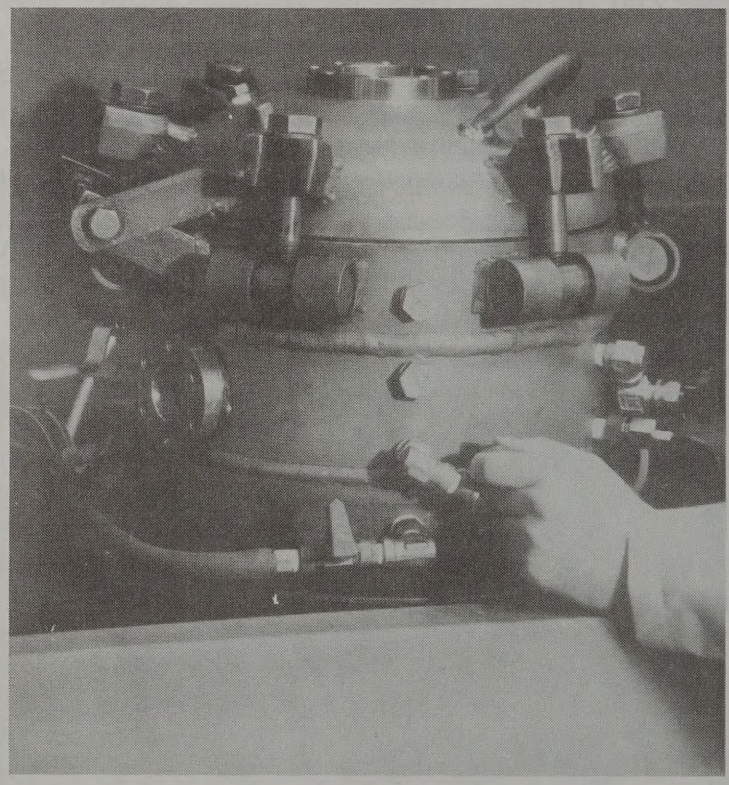


FIGURE 64. - The 20-liter explosibility test chamber is used to measure the flammability limits and rock dust inerting requirements for coal dusts and other mineral dusts.

peratures of dusts, their electrical ignitability, and the temperature dependence of the spark ignition energy. The new 6.8-liter ceramic furnace represents an improvement (fig. 65). The combined use of the autoignition furnace and the explosibility chamber has better delineated the relationship between flammability limits and thermal ignition properties for coals, oil shale dusts, and other industrial dusts and their dependence on concentrations, particle size, and rank (in the case of coal), and has contributed to the development of a general theory for the flammability of both heterogeneous dusts and homogeneous gases.

An important application of the carbon dioxide-powered laser to pyrolysis is being pursued by the Bureau. Data obtained have characterized rates of pyrolysis and devolatilization of coals and other polymers for radiant flux levels associated with dust explosions. These data, coupled with supporting data from the scanning electron microscope, clarify the physical processes taking place in coal particle devolatilization (fig. 66). The laser pyrolysis studies have successfully explained the measured particle size and rank dependence for the explosibility behavior of coals. Results from the studies with the laser and scanning electron microscope have application to efficient coal utilization for electric power generation. They also impact on the production of synthetic fuels and the thermal processing and use of minerals, mineral-derived products, and metals.

Bureau research has helped to elucidate the general mechanism for flame propagation in carbonaceous dust explosions. The preponderance of evidence supports the first step to be the pyrolysis and devolatilization of the fuel dust. Data have shown that the devolatilization rate limitations play an important role in the extinguishment, and more importantly, that commercially available powders, which were designed for fires, are much too coarse in diameter for optimum effectiveness against dust explosions.

Prevention and Suppression of Frictional Ignitions.—Studies conducted with the frictional ignition chamber and in field verification tests have indicated that implementing improved bit design, adhering to the optimal angle of attack, frequent replacing of worn bits, and most importantly, using back-mounted sprays significantly decreases the incidence of frictional ignitions (fig. 67).

Research has demonstrated that extinguishing agents, when rapidly dispersed from canisters mounted on continuous mining machines or longwall shearers, can effectively suppress incipient methane-air explosions.

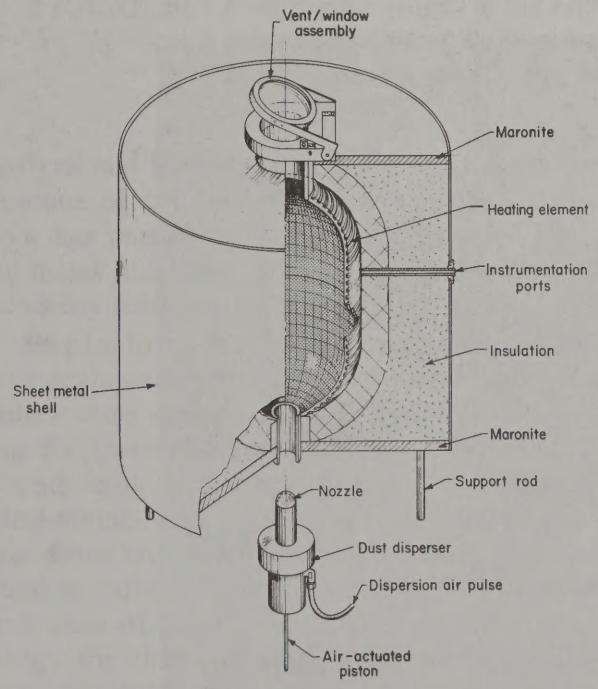


FIGURE 65. - New 6.8-liter furnace for measuring autoignition temperatures of dust clouds.

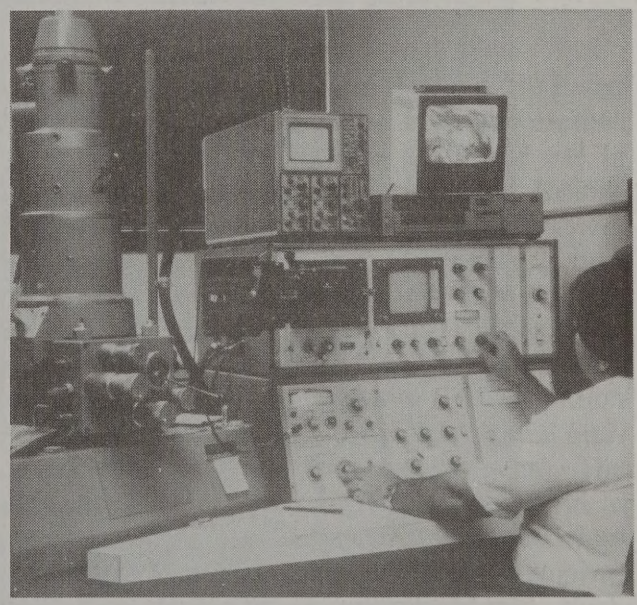


FIGURE 66. - Studying the residue from a dust explosion with a scanning electron microscope.

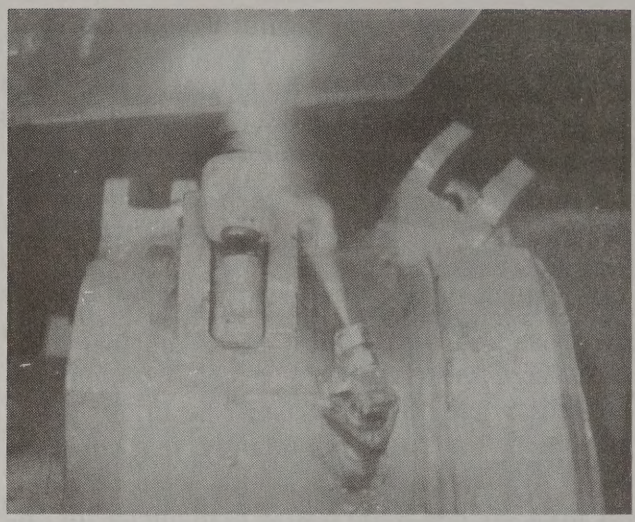


FIGURE 67. - Strategically mounted water spray cools the hot trace responsible for frictional ignition.

Measures To Supplement Generalized Rock Dusting.—Stacked passive rib barriers, utilizing German water tubs, can stop moderate-strength dust explosions in single entries when deployed between 60 and 100 meters from the ignition source. However, because of the considerable pressure relief in the room-and-pillar geometry, passive barriers can be easily defeated. The Bureau has developed an explosion-powered trigger barrier for use against gas and dust explosions (fig. 68). The new system uses a solar panel for converting the flame's radiation into electrical energy to fire explosion devices that rapidly release extinguishing agent into the propagating flame, suppressing the explosion.

Inflatable Flow Restrictors for Combating Emergencies.—The Bureau has developed lightweight inflatable bags for rapid control of air to and from a fire. Deployment can be accomplished underground or through boreholes (fig. 69). The bags show promise for remote filling with rapid-setting foam to become substantial seals.

Seals for Explosion Control.—The Bureau developed procedures for testing the performance of various types of explosion-proof seals against 20-psi methane-air explosions and measuring the leak rate. The results from these full-scale tests have been used by MSHA to develop policy statements on the deployment of substantial seals.

Safer Blasting in Gassy Noncoal Mines.—The Bureau conducted studies on the explosion hazard of oil shale dust. The work examined the flammability properties as a function of the particle size and kerogen content. The Bureau has developed and tested new low-incendive ex-

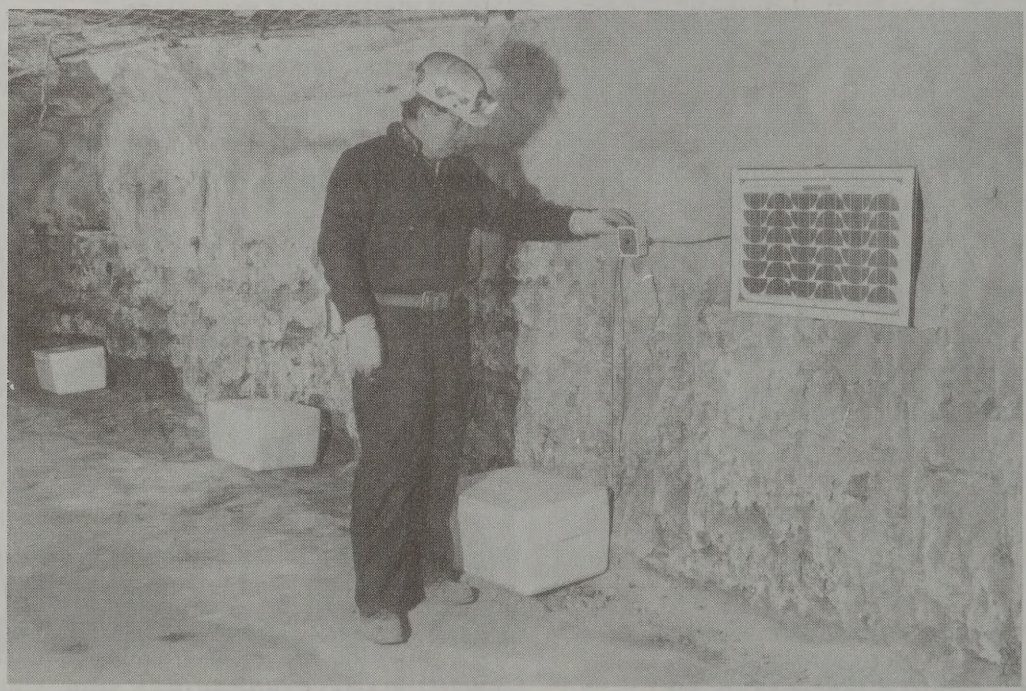


FIGURE 68. - Prototype explosion-powered triggered barrier for suppressing fully developed gas and dust explosions.

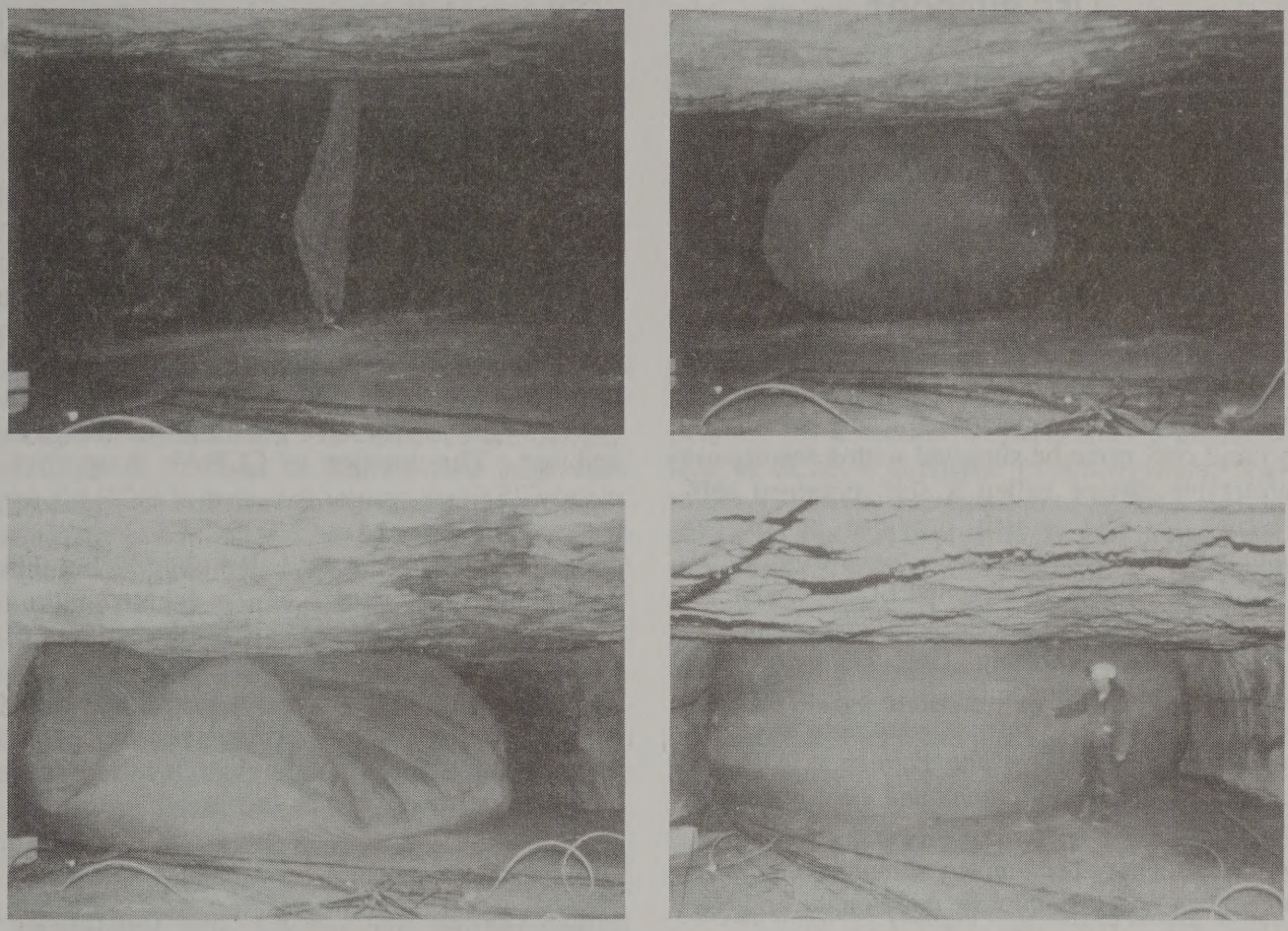


FIGURE 69. - Progressive stages in the remote deployment of an inflatable flow restrictor in a mine entry through a borehole. Such devices can rapidly isolate mine fire areas in the early stages of a fire and facilitate the recovery of mine personnel.

plosives and blasting agents for blasting in the presence of combustible gases and dust. The work has particular application to the oil shale and metal industries, which have problems with secondary sulfide dust explosions.

Explosion Research Facilities.—New large-scale underground and surface research facilities were erected at Lake Lynn Laboratory near Fairchance, Fayette County, PA. Underground explosion research can be conducted using single- and multiple-entry longwall configurations with wide roadways typical of those found in current operating mines. The facilities have state-of-the-art instrumentation and technology for characterizing all aspects of explosions, providing the Bureau with resources for explosion and mine fire research that are second to none in the world.

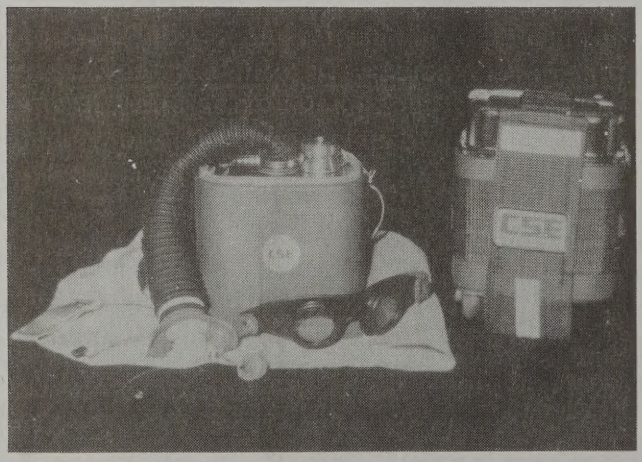
Instrumentation.—Over the years, to better diagnose explosion characteristics, the Bureau has developed new instrumentation for use in characterizing large- and small-scale explosions and devices. These include bidirectional gas velocity probes for characterizing turbulence, dust probes for characterizing dust clouds, flame-sensing probes (e.g., flame arrival probes, solar panel detectors for use with triggered barriers, and ultraviolet detectors for use with ignition suppression systems), heat flux probes, and optical pyrometers (3- and 6-wavelength units). The explosibility chamber has been most helpful in developing and evaluating instrumentation to characterize explosion parameters such as temperatures, dust cloud density, turbulence, etc. Such instrumentation has been reproduced by others and used domestically and internationally.

LIFE SUPPORT

Asphyxiation (suffocation) is a major cause of death in mining. After a mine fire or explosion, the atmosphere inside the mine may become oxygen-deficient or filled with smoke and toxic gases. Respiratory protection is necessary for successful escape from the mine. Filter self-rescuers have long been required in underground coal mines, but they only protect against low levels of carbon monoxide, not other toxic gases or low oxygen levels. Federal regulations now require that every person entering an underground coal mine be supplied with a respiratory protective device called a self-contained self-rescuer (SCSR), which provides an oxygen source and isolates the user's lungs from the atmosphere. Sixty-minute-rated SCSR's were introduced in U.S. underground coal mines in October 1982. During 1982-91, there were 12 U.S. underground mine fires and explosions in which at least 73 miners were able to escape by wearing SCSR's. The Bureau was instrumental in the development and deployment of SCSR's.

SCSR's have been mostly stored near the work area rather than continuously worn on the body because of their large size and weight. One way to improve survival odds was to reduce the size and weight of SCSR's so that they may be worn on the body at all times. The Bureau, through contract work performed by CSE Corp., Monroeville, PA, has reached new technological heights by developing a new, second-generation SCSR called the SR-100 (fig. 70). This 60-minute-rated SCSR is one-half the size and weight of the presently deployed SCSR's, but still twice as large and heavy as presently worn filter self-rescuers. In order to produce a third-generation SCSR that is the same size and weight as the filter self-rescuers, basic research into nonconventional oxygen storage and membrane oxygen extraction technology must be undertaken.

Because of the long distances involved in both escape and rescue, closed-circuit breathing apparatus (CCBA's) have always been preferred in mining over open-circuit breathing apparatus (OCBA's) in which each breath is exhausted to ambient. The duration of CCBA's is approximately 25 times greater than that of OCBA's for the same quantity of stored gas. CCBA's recycle exhaled air to reuse exhaled oxygen, but this necessitates the removal of the exhaled carbon dioxide from the breathing circuit through use of a chemical bed, adding heat to the breathing gas. The chemical bed that absorbs the carbon dioxide also causes high breathing resistance and may permit higher-than-ambient levels of carbon dioxide to remain in the breathing circuit.



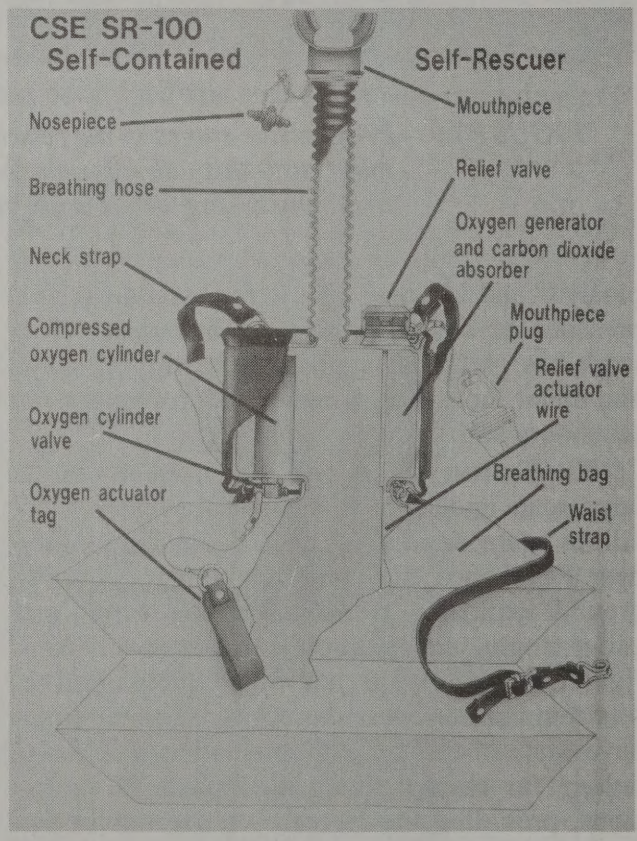


FIGURE 70. - The SR-100 is a belt-wearable respiratory protective device developed by the Bureau of Mines and CSE Corp. for escape from mine fires and explosions.

Open-circuit devices do not suffer from these problems and are widely preferred outside of mining, mostly in the fire service.

The physiological stressors imposed by CCBA's—the higher-than-ambient levels of breathing resistance, temperature, and carbon dioxide—will, at some point, negatively affect physiological and mental performance during escape and rescue. It is the goal of breathing apparatus developers to keep the physiological stressors as low as possible for the full duration while also keeping the size and weight of the apparatus at a minimum. To optimize the design of CCBA's, it must be known how high the physiological stressors can go before negatively affecting performance. Since CCBA's are not widely used outside of mining, the effects of their physiological stressors have not been studied outside of Bureau efforts. The Bureau has been sponsoring investigations into this area for 2 decades. The information gained will provide the basis for recommendations for revisions to the Federal CCBA approval regulations. This is expected to result in smaller, lighter, and safer apparatus.

In a related area, the Bureau evaluates CCBA's exposed to the underground mining environment or actually used in mine emergencies, as well as those under development in prototype configuration. Most of this research entails the use of a breathing and metabolic simulator (BMS) for the testing of these apparatus (fig. 71). The Bureau developed the BMS after 15 years of research and testing. Before the development of a BMS, it was not possible to objectively evaluate the performance of breathing apparatus, for human subject testing does not provide a sufficiently quantitative or repeatable metabolic load on such apparatus. Quantitative and repeatable testing is necessary for a number of important tasks: (1) a level performance comparison of rescue and escape breathing apparatus, (2) detection of performance degradation in SCSR's deployed in underground coal mines, (3) forensic evaluation of SCSR's used in actual escape, (4) evaluation of prototype apparatus, and (5) testing for certification. The BMS design concept developed by the Bureau has been duplicated by other government agencies and breathing apparatus manufacturers. However, the design specifics, as well as the development of test methods and standards, remain to be determined.

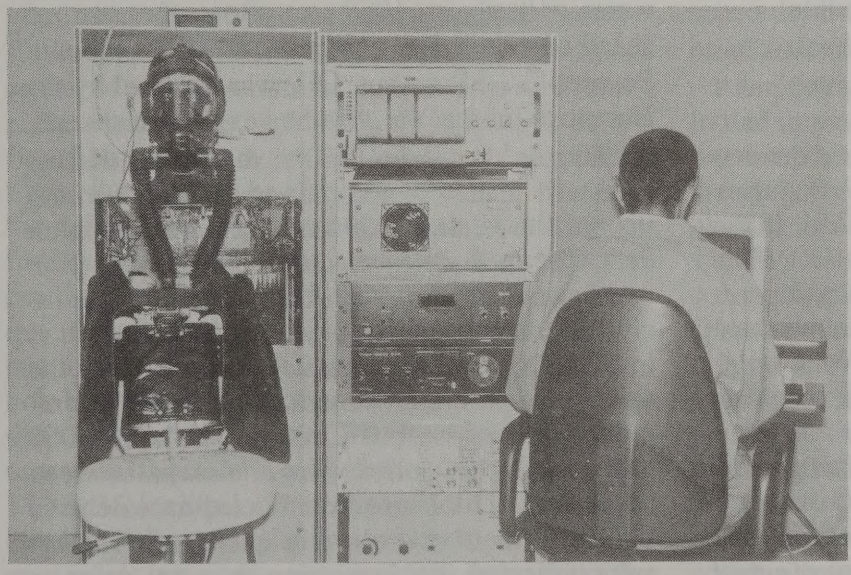


FIGURE 71. - The Bureau's breathing and metabolic simulator is used to test closed-circuit breathing apparatus with more control and repeatability than is possible with human test subjects.

EXPLOSIVES

The thrust of Bureau explosives research has remained essentially the same since passage of the 1969 Act. As has been the case since the Bureau's establishment in 1910, a major part of the explosives effort has been directed toward ensuring the safety of permissible explosives used in underground coal mines. New explosives intended for use in underground coal mines were evaluated according to the test schedule specified in Title 30 of the Code of Federal Regulations and subsequently approved as "permissible" if they passed all tests. Research continued into the development of improved tests for evaluating the tendency for explosives to ignite flammable gas and dust atmospheres.

A major thrust of explosives research was establishing the safety of a new class of permissible explosives—water gels—that had been developed by industry. Initial evaluation of

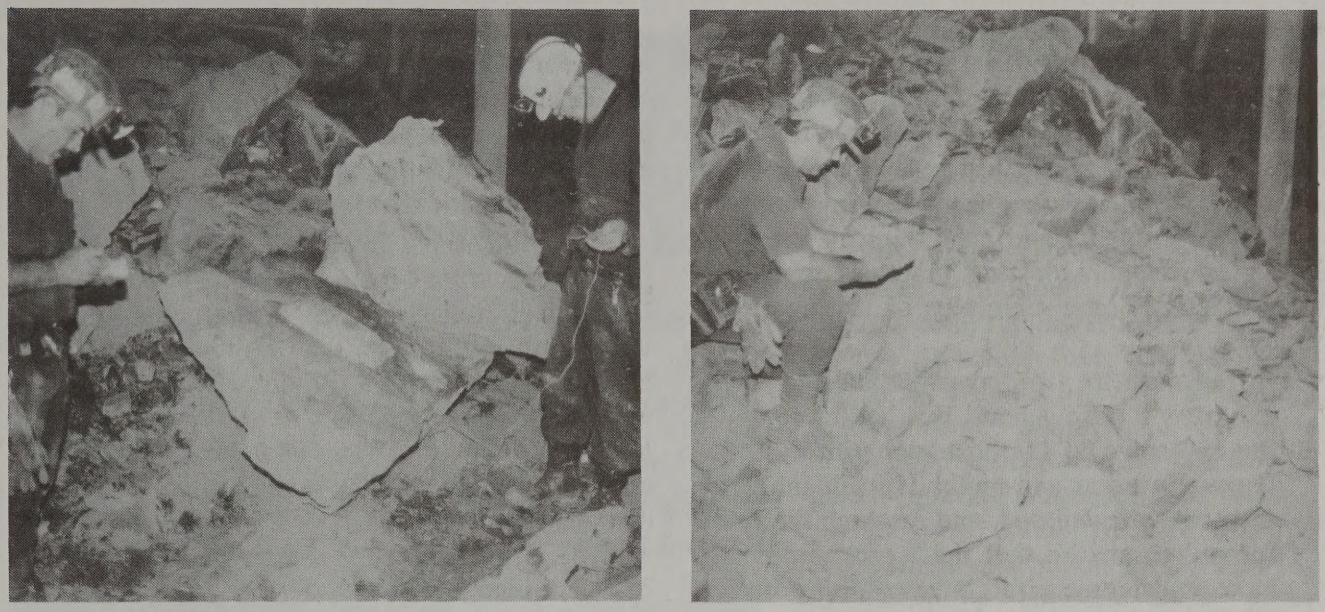
these explosives suggested that they possessed an increased tendency to ignite coal dust and gas mixtures compared with traditional permissible explosives. This observation sparked the development of a new gallery test. The existing gallery test 4 evaluated the tendency for an explosive to ignite coal dust placed in trays in the gallery in the presence of 4% natural gas. For the new gallery test 8, the coal dust was predispersed in the 4% natural gas atmosphere, which represented a more realistic test. Gallery test 8 replaced test 4 in the revised permissible explosive test schedule published in 1989.

Research over the last 20 years led to other changes that were incorporated into the 1989 revisions to the permissible explosive approval schedules and regulations governing blasting in underground coal mines. The toxic fumes produced by the detonation of permissible explosives have traditionally been evaluated using the Crawshaw-Jones apparatus and the Bichel Gauge. These are apparatus in which explosive samples are detonated in a small volume and fume samples are taken for laboratory analysis. A new test was developed to better simulate the behavior of explosive fumes in an underground coal mine. Here, the fumes from the explosive are allowed to expand into a 38,500-cubic-meter steel chamber. This new Large Chamber Fumes Test has now replaced the traditional Crawshaw-Jones and Bichel Gauge techniques in the approval schedule.

The sensitivity of permissible explosives has traditionally been evaluated in the Bureau's Air Gap Test. In this test, an explosive is cut in half, one half is primed with a No. 6 electric detonator, and the ability of the explosive to propagate a detonation from one half of the cartridge to the other across an open space is evaluated. This test had become obsolete over the years for two reasons. First, blasting in underground coal mines is no longer conducted using No. 6 detonators, but rather stronger No. 8 detonators. Second, the test was developed at a time when most permissible explosives were nitroglycerine-sensitized. Usage temperature had little effect on these explosives, but this is not the case for the water-gel explosives and the newer emulsion explosives. At low winter temperatures, the water-gel and emulsion explosives may not detonate properly, and in some cases, may not detonate at all. The 1989 revision to the approval schedule included modifications to the Air Gap Test to incorporate the use of a No. 8 detonator and evaluation of the performance of the explosive at low temperatures.

The regulations governing blasting in underground coal mines have long prohibited the firing of unconfined explosive charges owing to the possibility of igniting flammable gas and coal dust that may be present. The only legal way to shoot explosives was in stemmed boreholes. It was well known, however, that blasters were continuing to shoot unconfined explosive charges, termed "mud caps" or "adobes," in underground coal mines to break up large stones. They continued to utilize this illegal practice because it was much easier than bringing in a drill to drill shotholes. Recognizing this, the Bureau began research to develop a sheathed explosive charge that could be safely fired unconfined in a potentially flammable atmosphere without causing an ignition. This charge would be used to break up large stones without the need to drill boreholes (fig. 72). This research resulted in the development of schedule tests for the approval of sheathed explosive charges as permissible. This test schedule was included in the 1989 revision to the MSHA permissible explosive approval schedule. Additionally, the regulations governing blasting in underground coal mines were revised in 1989 to allow the use of sheathed explosive charges. In 1989, Austin Powder Co., McArthur, OH, was licensed by the Bureau to market the sheathed explosive charge.

During the early 1980's, there was discussion within the blasting community concerning the need to retain the 500-millisecond maximum delay for short-delay electric detonators used in underground coal mines. This limitation was included in the definition of short-delay detonators in 30 CFR 25. Many blasters believed that the safety of coal mine delay blasting would be improved if the maximum delay was set at 1,000 milliseconds to permit longer delays between boreholes. The Bureau conducted an extensive field project to address this question. The results indicated that increasing the total delay to 1,000 milliseconds would not adversely impact



BEFORE *AFTER*

FIGURE 72. - The effectiveness of the Bureau-developed sheathed explosive charge in breaking up boulders is shown in these before and after photographs.

safety. This increase was incorporated into the 1989 revision to 30 CFR 75.

At about the same time of this field study into maximum delay time, MSHA and the Bureau became aware of unsubstantiated reports that permissible explosives were frequently misfiring. To verify this, a limited research program was conducted at the Bureau's Safety Research Coal Mine at Bruceton, PA. In a series of eight test shots, it was observed that some permissible explosives do frequently misfire if boreholes are spaced too closely together. Since the Bureau had access to a field site for the delay time study, a program was initiated to further study the spacing question. Results indicated that some permissible explosives frequently misfired at a hole spacing of 18 inches, but tended to misfire much less frequently at a hole spacing of 24 inches. Based on these data, the 1989 revision to 30 CFR 75 reflected an increase in the minimum borehole spacing from 18 to 24 inches. This change did not totally eliminate the potential for misfired permissible explosives, so a research program was initiated to develop a better understanding of the problem. Based on this research, it was determined that some permissible explosives misfired because they were physically damaged by shockwaves produced by earlier-firing boreholes. A simulator was developed to evaluate the susceptibility of various permissible explosives to this type of damage. This test was not included in the permissible explosive approval schedule, but research is continuing and it may be included at some future time.

In addition to ensuring the safety of blasting in underground coal mines, the Bureau has been involved in a wide range of other research addressing the needs of the Nation's mining and blasting industry. For instance, in 1974, in response to both the direct fuel shortage and the consequent anticipated shortage of fuel-derived chemical feedstocks for producing ammonium nitrate, the principal ingredient of explosives and blasting agents, research was directed into the development and characterization of explosive formulations that would detonate in thin layers for oil and gas well explosive tracking operations and into determining the extent to which alternative oxidizers could be substituted for ammonium nitrate in explosives and blasting agents. In related research, an incident involv-

ing the premature detonation of an explosive charge by the reaction of ammonium nitrate with sulfide ore led to an evaluation of the effectiveness of various inhibitors of this reaction.

Much of the Bureau's research has been directed toward assisting in the determination of explosive accidents and evaluating new explosive products and blasting practices to ensure their safety. Some examples of this research follow:

- In response to a proposed scheme to "tag" explosives with agents that could identify the explosive by the postdetonation residue, taggant systems and methods for identifying them were developed, and research was performed to ensure that the taggants did not have an adverse effect on sensitivity or the tendency to ignite flammable atmospheres.
- After an accident related to the introduction of a novel system for transmitting initiation of detonation, an exhaustive investigation revealed that the problem was sensitivity to electrostatic energy, and the manufacturer remedied the problem.
- Owing to an accidental explosion involving the transportation of a large quantity of a supposedly nonexplosive sensitizing agent used in water-gel explosives, the Bureau developed a test procedure that simulates real-world conditions not seen in standard explosive test procedures. The procedure revealed that the potential for the accident could have been predicted, and it can be used as a screening test for other materials of this type.
- With the introduction of another new class of explosives (binary explosives), the Bureau initiated research on the safety characteristics of the individual component materials.
- With the introduction of pneumatic explosive cartridge loading equipment, the Bureau conducted research to determine whether cartridges could accidentally be propelled with a velocity that might cause initiation of the cartridge when it struck the bottom of the borehole.
- In response to the introduction of plastic-wrapped explosive cartridges sealed with metal clips, the Bureau conducted research to determine whether the metal clips posed a hazard. The results of this study led to the specification of safe construction of the clips.
- At one time, explosives were loaded through the hollow stem of a borehole drill in ground conditions in which the borehole collapsed as the drill was withdrawn; accidents occurred when the explosives jammed in the drill stem and detonated during attempts to free them. The Bureau developed a technique in which an expendable, rigid borehole liner could be introduced to retain the hole while the drill is withdrawn, with the explosives loaded afterward.
- After an accident in which a man was killed in a mine entry by a blast wave at a great distance from the source explosion, the Bureau undertook a research project to determine the attenuation of a blast wave as it propagates in mine entries so that safe distances can be specified.
- As a result of several accidents in which explosives were prematurely detonated by lightning, the Bureau undertook a project to evaluate commercially available lightning warning systems to determine whether they would give suitable warning of lightning in advance (fig. 73).
- With the occurrence of several accidents in which explosives were prematurely detonated by mechanical or unknown means (probably electrostatic), the Bureau undertook the novel development of a detonator that obviates the need for using very sensitive explosives and that is much less sensitive than conventional detonators to both mechanical and stray electrical stimuli. Additionally, the Bureau undertook a research project to simulate the mechanical activities (drilling and mucking) to which explosives and detonators are most often inadvertently subjected to establish the relative safety of various types of explosive products in these environments and to verify the adequacy of laboratory tests for their sensitivity.

In cooperation with and using funding provided by the U.S. Department of Transportation (DOT), the Bureau conducted extensive research in support of a new classification system for explosives being developed in conjunction with the United Nations. Several of the tests incorpo-

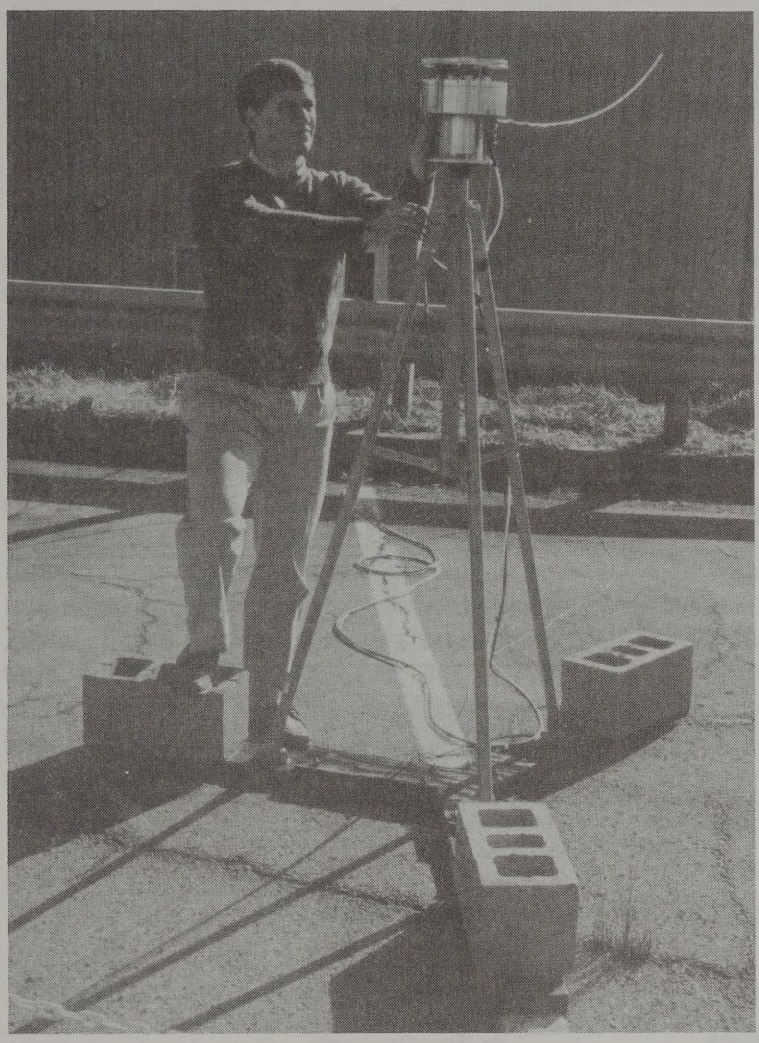


FIGURE 73. - A Bureau researcher checks the connection on an electric field mill lightning warning system.

rated into this classification system were developed by the Bureau. The Bureau evaluated all of the tests to ensure that they properly assessed the hazards associated with explosives without having an undue negative impact on the U.S. explosive industry. The resultant classification procedures have ensured that U.S. mine safety standards pertaining to the use of explosives have not been impacted by this international standardization effort.

Analysis of blasting accident statistics was begun by the Bureau in 1978 to identify accident causes and areas of needed research that could be addressed through blast design and improved work practices and procedures. This accident analysis has continued, with data for 1978-89 now published. Injuries from blasting accidents have declined, with 50% fewer injuries now than there were in the 1970's. The most frequent causes of blasting accidents are failure of blast area security during production blasting, premature blasts, flyrock, fumes, and misfires.

Research to develop safer blasting practices included five Bureau-funded contracts awarded in 1978-81 on use of safety fuse, boulder blasting, blast area security, measurement of stemming height and blasthole depth, and procedures for blasting in gassy noncoal underground mines. An in-house study of safe blasting procedures was begun in 1982 owing to additional concern about gassy mines fueled by renewed interest in oil shale mining. In 1984, the Bureau initiated a multiphase study with funding from three different programs to develop a blaster's training manual, blast designs that reduce rock fall hazards by producing less fracturing and overbreak, and further study of three areas identified as responsible for most blasting accident fatalities: blast area security, flyrock, and misfires. Because blasting accidents continue and explosives are expected to remain the primary means for fragmenting rock in the foreseeable future, the Bureau will continue research to develop safer explosives and blasting procedures.

MINE RESCUE

As a result of a research study of mine disaster survival and rescue, trapped miner location and communication systems were developed to enhance the miner's chances of survival after a mine disaster such as a fire or explosion. Initial work focused on seismic and electromagnetic methods of detecting trapped miners from the surface and communicating with them. Borehole probes and hoist phones were developed that assisted rescuers in determining in-mine conditions and entering the mine more rapidly. A rescue team in-mine vehicle was developed and evaluated.

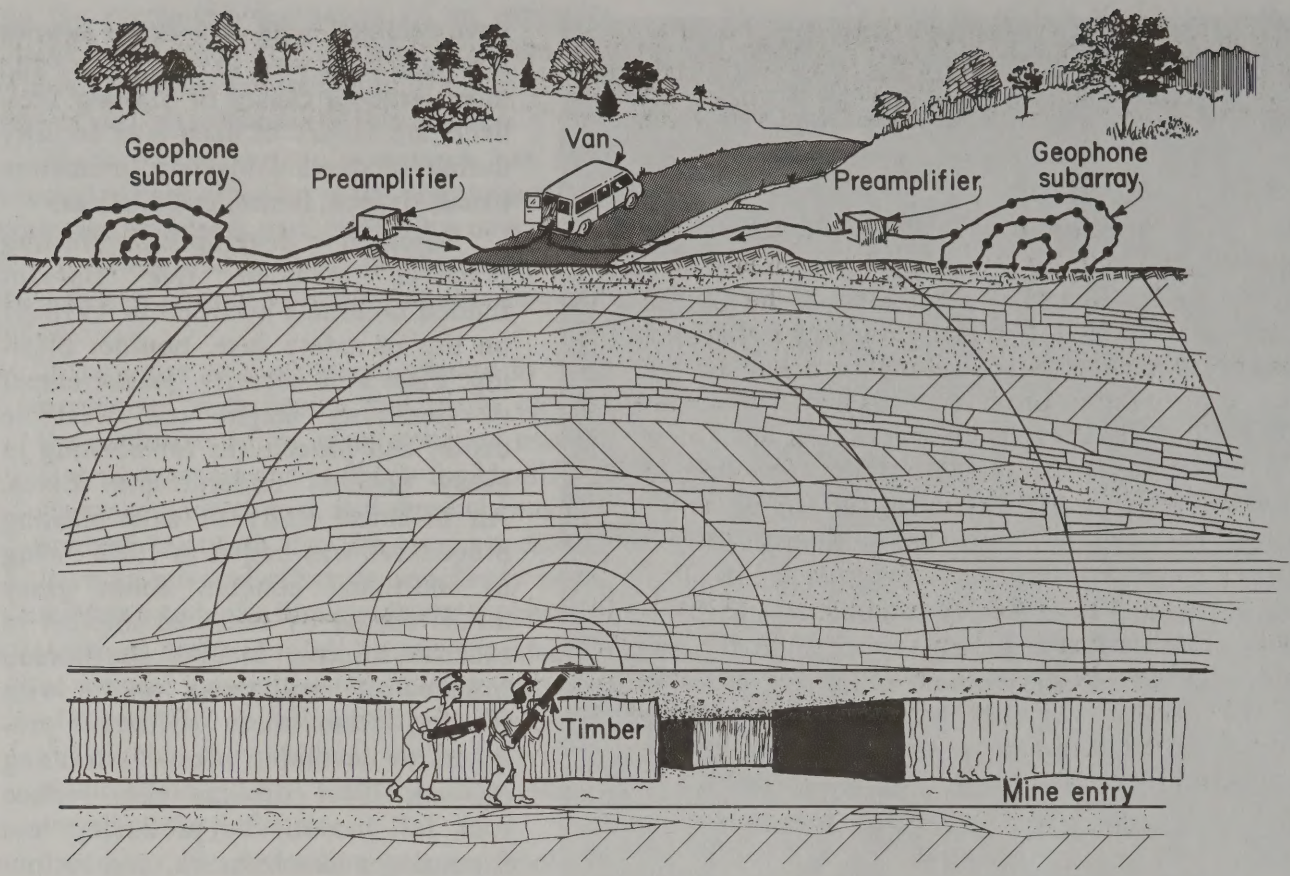


FIGURE 74. - Seismic system for locating trapped miners.

Other research led to the development of a whole-mine medium-frequency radio system that provides in-mine communications wherever conductors or metallic structures, such as power lines, water pipes, rails, etc., ran in the mine. These structures provide the transmission network for the radios such that trapped miners and rescue teams can communicate under postdisaster conditions. The seismic system (fig. 74), borehole probe (fig. 75), and hoist phone offer improved capability for rescue teams to respond to mine disasters. The medium-frequency system is now a commercial product produced by Stolar, Inc., that is in operation in a major western U.S. mine.

Lastly, the True Flammable Gas Detector system was developed, which allows rescue team workers to monitor the concentration of explosive gases up to 100% using a catalytic heat-of-combustion sensor.

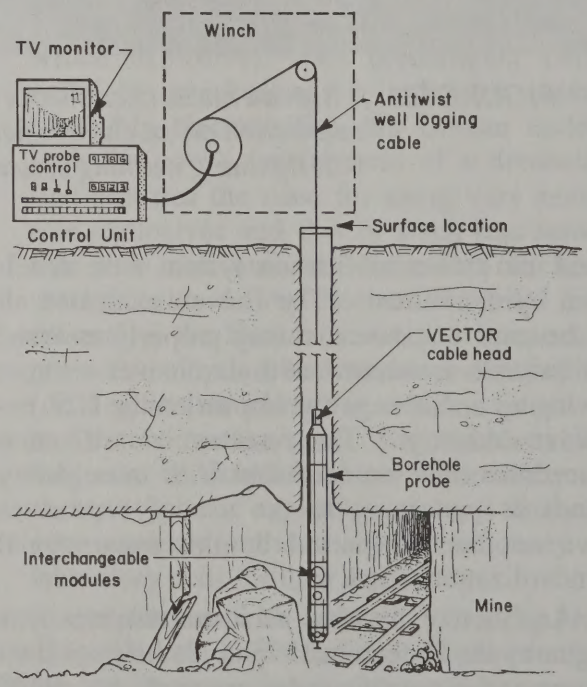


FIGURE 75. - Borehole probe application concept.

THE FUTURE

The Bureau of Mines health and safety program has reached a high degree of maturity, with numerous techniques and procedures already in use or approaching the point where they can be applied by the industry. Nevertheless, the Bureau's health and safety program faces a number of challenges and opportunities. Changing mining conditions, such as deeper and thinner deposits with unstable formations, will continue to dictate the need for improvements in existing mining processes. Also, growing mine production has increased the need for new or alternative methods to maintain current health and safety achievements. As our Nation continues to strive for energy independence and minimal dependence on foreign sources of supply for metal and nonmetal mined products, we must do so with a reduced toll on human suffering. As we compete in an international marketplace, where many other countries do not have strong health and safety or environmental requirements and where financial compensation for miners is substantially less than in the United States, we are challenged to meet the recently established MSHA health and safety goal—zero fatalities by the year 2000. These accomplishments can only be realized through a balanced program consisting of long-term, high-risk, basic research coupled with shorter-term studies addressing immediate health and safety concerns. The Bureau is committed to addressing our Nation's needs through new and radical approaches that will provide the technology and the means necessary for continued improvements in mine health and safety.

FOR MORE INFORMATION

The achievements of the Bureau's health and safety research program since the enactment of the Federal Coal Mine Health and Safety Act of 1969 have been summarized in this publication. Additional information may be obtained by contacting:

Associate Director—Research
U.S. Bureau of Mines
810 7th Street, N.W.
Washington, DC 20241

SELECTED BIBLIOGRAPHY

Results of Bureau research are published as Reports of Investigations (RI's), Information Circulars (IC's), and Bulletins. Single copies of recent RI's, IC's, and Bulletins are available at no cost and may be obtained by writing:

Publications Distribution
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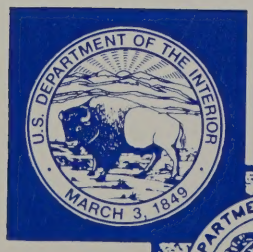

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